applied sciences

MDPI

Article

Unilateral Drop Jump Kinetics and Kinematics Differentiate Patellofemoral Pain Patients from Healthy Controls

Germari Deysel , Mariaan van Aswegen and Mark Kramer *

Physical Activity, Sport, and Recreation (PhASRec) Research Focus Area, North-West University, Potchefstroom 2531, South Africa; germari.bos@gmail.com (G.D.); mariaan.stofberg@nwu.ac.za (M.v.A.)
* Correspondence: mark.kramer@nwu.ac.za; Tel.: +27-018-285-2625

Abstract: The diagnosis of patellofemoral pain (PFP) remains imprecise due to the variable sensitivity and specificity scores of most clinical tests. More functionally relevant assessments and metrics are needed to provide better diagnostic insights. A total of 33 participants (control: n = 17 [M/F = 9/7]; PFP: n = 18 [M/F = 2/14]) volunteered for this study. The control group followed no intervention program, whereas the PFP group completed a joint-specific intervention program at a clinical practice for 8 weeks. At 0- and 8-week isometric knee extensor torques, unilateral drop jumping metrics, and anterior knee pain scale (AKPS) scores were collected and analysed. Statistically significant between-group differences were evident for the reactive strength index (RSI) (M_{diff} = 0.05 m/s, p = 0.032) and ground contact time (GCT) (M_{diff} = 0.28 s, p = 0.011) but not for peak force (p = 0.390), jump height (p = 0.721), impulse (p = 0.740), or peak torque (p = 0.359). While controlling for gender as a confounder, the RSI and GCT showed diagnostic utility for differentiating PFP from healthy controls (AUC = 0.83–0.87, sensitivity = 0.85–0.91, and specificity = 0.59–0.72). The AKPS score demonstrated moderate positive correlations with jump metrics (impulse: r = 0.58, 95% confidence interval (CI) [0.11, 0.83]; RSI: r = 0.50, 95% CI [0.01, 0.80]), accounting for 25–34% of performance variability. The unilateral drop jump provides useful metrics for differentiating those with PFP from their healthy counterparts. The RSI and GCT may serve as diagnostic metrics in evaluating PFP patients and can be coupled with the AKPS to track performance and rehabilitation progress in PFP patients.

Keywords: classification; jumping; sensitivity; specificity

Citation: Deysel, G.; van Aswegen, M.; Kramer, M. Unilateral Drop Jump Kinetics and Kinematics Differentiate Patellofemoral Pain Patients from Healthy Controls. *Appl. Sci.* **2024**, *14*, 11058. https://doi.org/10.3390/app142311058

Academic Editors: Claudio Belvedere and Arkady Voloshin

Received: 6 October 2024
Revised: 16 November 2024
Accepted: 26 November 2024
Published: 27 November 2024

1. Introduction

Patellofemoral pain (PFP) is a multifactorial condition broadly associated with anterior knee pain that likely stems from altered biomechanical dynamics, causing a loss of tissue homeostasis rather than actual damage to the knee [1,2]. Moreover, it is a condition that affects both athletic and sedentary populations, accounting for 25–40% of knee complications reported in sports injury clinics [3,4] and 12–17% in general practice [5]. The evaluation and diagnosis of PFP, however, remains imprecise due to the variable sensitivity and specificity scores of most clinical tests, which typically rely on a combination of patient history (e.g., age, activity), physical examination (e.g., patellar tilt, Q-angle, crepitus, strength), and functional testing (e.g., squatting, lunging, stair descent) [4,6–8]. If the provocation of symptoms is a key factor in the evaluation process, then functional movements that intensify knee joint loading, such as squatting and jumping, should be selected [9]. More specifically, weight-bearing exercises involving higher knee flexion angles, such as countermovement (CMJ) and/or drop jumping (DJ) manoeuvres, tend to generate higher patellofemoral loads and would therefore be good candidates for differentiating those with PFP from those who do not [9,10]. Recent research has shown that the unilateral DJ typically yields higher patellofemoral joint peak forces (6.6 ± 1.8 bodyweights) compared to the unilateral CMJ (6.4 ± 1.1 bodyweights), yet the use of the DJ within the evaluation of PFP cohorts has received limited attention [9]. Whether the functional assessment of clinically compromised groups could be enhanced with the use of newer technologies such as force plates that can provide access to insightful metrics linked to nuanced variations and compensations in performance has also received limited attention [11]. Moreover, to ensure an unbiased and consistent assessment, any test or metric used in the evaluation of PFP should be standardized and independent of the specific exercise or rehabilitation program implemented. This means that the evaluation tools must not be influenced by variations in rehabilitation protocols, allowing for accurate comparisons and reliable measurements of patient outcomes. As such, the literature has shown that metrics such jumping height, ground contact time (GCT), the reactive strength index (RSI), and impulse exhibit high levels of consistency (ICC = 0.85, 0.94, 0.87, and 0.91, respectively), thereby making these reliable metrics to track performance [12]. Presently, no research has evaluated whether jumping-based force plate metrics could provide diagnostic insights for distinguishing PFP patients from healthy controls by providing performance thresholds, thereby presenting a gap in the current literature.

Given that people with PFP experience more physical, emotional, and social limitations during sport activities and activities of daily living [13] and PFP may persist over several years [14] and may lead to patellofemoral osteoarthritis [15], early identification and rehabilitation is important. The need for better diagnostic tools is also motivated by the fact that, despite a large body of research dedicated to PFP, the recurrence rates remain high (40–79%) [14,16]. Although multiple factors may contribute toward the development of PFP, the evaluation of PFP should also be qualitatively evaluated through the use of questionnaires, such as the anterior knee pain scale (AKPS), to capture patient-specific perceptions of pain and functional performance outcomes. The AKPS is a validated questionnaire used to determine the functional disability of PFP patients [17], but presently, no research has evaluated whether AKPS scores are associated with kinetic and kinematic variables in people with PFP, thereby requiring further research.

The objectives of the study were four-fold: firstly, to evaluate within- and between-group differences for force-plate-derived kinetic and kinematic variables during unilateral drop jumping; secondly, to evaluate the diagnostic capacity of key force plate-derived metrics for differentiating PFP patients from healthy controls; thirdly, to establish performance thresholds that optimise between-group differences that may further facilitate clinical evaluations of PFP patients and healthy individuals; and finally, to determine the correlations between kinetic and kinematic performance metrics and subjective AKPS scores in patients with PFP, aiming to improve clinical assessment protocols which may guide rehabilitation interventions.

2. Materials and Methods

2.1. Study Design

A repeated-measures design was used, consisting of a combination of between- and within-subject factors [18]. The between-subjects independent variable was group allocation (control group and PFP group) where group assignment was not randomised but rather specifically divided into the presence or absence of injury. A control group was used to compare data from the PFP group to evaluate testing consistency. The within-subjects independent variables were time (repeated measures), and extremity (injured/non-dominant and uninjured/dominant lower limb).

2.2. Participants

A minimum sample size of 24 was calculated based on a repeated-measures analysis of variance design that incorporated (i) a within-between interaction, (ii) a moderate effect size (f = 0.25), (iii) a type-I error rate of 5% ($\alpha = 0.05$), (iv) a type-II error rate of 20% ($\beta = 0.20$), (v) 2 groups (control and PFP), (vi) 2 repeated measurements, and (vii) a minimum expected correlation of 0.50 among the repeated measurements [19,20]. A total of 35 participants volunteered for the study, of which 17 were part of the control group (female [n = 10] and male [n = 7]) and 18 were part of the PFP group (female [n = 15] and male [n = 3]). Accounting for a potential drop-out of 20%, the minimum sample size for adequate statistical power was 29 participants. Participants were recruited using a combination of information flyers and patient referrals from various rehabilitation and performance clinics throughout the region where the study was conducted. Two participants were lost to follow-up, both in the PFP group (female [n = 1] and male [n = 1]), due to incomplete data, resulting in a final sample size of 33 participants.

The inclusion criteria for the PFP group consisted of the following: (i) aged between 18 and 35 years, (ii) could be male or female, (iii) had to exhibit retropatellar and/or peripatellar pain aggravated by at least one activity that loads the patellofemoral joint during weight bearing on a flexed knee, such as squatting, stair climbing, jogging/running, and hopping/jumping, and (iv) had to participate in some form of rehabilitation program with any practitioner of choice. The inclusion criteria for the control group were the same, with the exception of points (iii) and (iv).

The specific exclusion criteria for both groups consisted of the following: participants should not (i) have had previous patellar dislocation or subluxation, (ii) have had previous injury to or surgery on the knee, and (iii) have had recent (within the last 6 months) injury to the lower limbs (e.g., Achilles tendinopathies, ankle sprain, etc.).

2.3. Procedures

A general demographic questionnaire was completed first during the physical examination at our rehabilitation clinic to obtain the participant's contact details, e-mail address, age, sex, involved limb, dominant limb, previous injuries and PFP symptoms. Thereafter, the anterior knee pain scale (AKPS), also known as the Kujula patellofemoral scoring system, was completed verbally to capture knee-related pathologies where the total score out of 100 was captured electronically. The AKPS was the chosen questionnaire, as it was developed specifically for the evaluation of pain and disability in individuals with PFP [17], showed high test–retest reliability (intraclass correlation coefficient [ICC] = 0.95), and exhibited moderate responsiveness to clinical change, which implies that the score will likely reflect meaningful changes in a patient's condition over time [21].

Body mass and stature were then measured to standardise the effect of jump–landing forces across individuals [22]. Body mass was measured to the nearest 0.1 kg with an electronic scale (Seca 874, Seca, Hamburg, Germany) and stature with a portable stadiometer (Holtain Ltd., Crymych, UK).

A cycle ergometer (Wattbike Pro, Wattbike Ltd., Nottingham, UK) was used for a ten-minute warm-up at a light effort (RPE = 2; modified Borg scale) prior to the testing for optimal muscle performance and a reduced risk of injury [23].

After the warm-up, the isometric strength of the knee extensor muscle group was assessed on an isokinetic dynamometer (Cybex HUMAC Norm II, model CSMi 6000, Stoughton, MA, USA) which recorded torque data at 100 Hz. Participants were set up on the isokinetic dynamometer according to manufacturer's instructions, where the dominant side in the control group and the uninjured side in the PFP group were measured first. Briefly, the participant was seated with the rotation scale, fore–aft positions, and monorail of the rig adjusted such that the axis of rotation of the dynamometer was aligned with the centre of the knee joint axis. Gravity correction was performed to account for any potential additional torque induced on the attachment. The knee was positioned at an angle of 60° relative to anatomical zero, and the participants were then required to exert maximal knee extension force against the movable arm of the dynamometer for five seconds per trial. A total of three familiarisation trials with a 30 s rest period between trials preceded the actual trials, whereafter a one-minute rest period was granted. A total of 5 maximum effort isometric test trials lasting 5 s were recorded for each limb, and pain levels were monitored by asking the participant to rate pain on a scale of 1–10 throughout the procedure (where 1 = pain free, 2 = very mild, 3 = discomforting, 4 = tolerable, 5 = very distressing, 6 = intense, 7 = very intense, 8 = utterly horrible, 9 = excruciating/unbearable, 10 = unimaginable/unspeakable) [24]. Participants were permitted to stop the test if pain levels were above bearable levels (≥4), although no such instances were recorded. To ensure that maximal efforts were consistently applied across trials, the coefficient of variation was evaluated on the dynamometer and had to be ≤5%, which was achieved by all participants. The raw torque–time data were exported to Matlab (version R2023b, The Mathworks, Natick, MA, USA) for processing, where all trials were ensemble-averaged and the peak torque values retained for analysis.

The evaluation of the unilateral drop jump (DJ) was then completed on a tri-axial force plate (AMTI, Watertown, MA, USA), which was used to measure ground reaction force at a sampling frequency of 2000 Hz. Participants completed three familiarisation trials on each leg prior to the test and were granted two minutes of rest to ensure complete recovery before starting with the data collection. Participants followed the protocol outlined by Ortiz et al. [25], with only the DJ height being modified according to the recommendations by Wang and Peng [26]. The unilateral DJ was used since it evaluates the eccentric loading of the lower extremities to a greater extent, thereby more likely stressing the patellofemoral joint to accentuate inherent differences between groups [26]. The unilateral DJ was performed by standing with both feet on a 0.25 m platform with hands on hips. On the instruction "drop", the participants dropped off the platform by leaning forward and landed on the jumping leg on the centre of the force plate followed by a maximal-effort vertical jump immediately upon landing. Participants were also cued to "to jump as high as you can after landing" in order to standardise the instructions as this could influence performance [27]. Instructions to "drop" off the step (i.e., not jumping off) can influence the actual drop height; this was verified by a visual inspection of the video data collected at the same time. All video data were inspected by the same examiner (GD) for all trials to standardize the testing procedures. Participants were permitted one minute of rest between repetitions and were required to complete three repetitions of the unilateral DJ on each leg. The best trial, according to jump height, was used in the final assessment. Trials were discarded and subsequently repeated if (i) a noticeable 'jump' was performed off the platform, (ii) participants lost balance on landing, and/or (iii) they jumped/stepped off the force platform following the second landing. The raw force–time data were exported to Matlab (The Mathworks, Natick, MA, USA) for processing. The force data were smoothed using a 4th-order, zero-lag Butterworth filter with a cutoff frequency of 50 Hz. The force data were 'flipped' such that the last data point became the first, thereby allowing for the application of Newton's second law to calculate the inverse dynamics associated with the jump (e.g., acceleration–, velocity–, and displacement–time curves) through mathematical integration [28]. Jump height was calculated using the vertical velocity of the centre of mass at take-off [29]. The reactive strength index (RSI) was calculated as the ratio of vertical jump height and ground contact time, the latter being defined as the time (in seconds) from the initial ground contact to take-off [28]. The impulse was calculated as the area under the force–time curve during ground contact, and peak force was simply the maximal force recorded during the contact phase of the drop jump.

2.4. Intervention

Following baseline testing, an 8-week intervention period was initiated. The control group followed no intervention program, whereas the PFP group completed an intervention program at a clinical practice of their choice. Most programs included the strengthening and stretching of the quadriceps, gluteus, and hamstring musculature, as well as proprioceptive exercises that encompassed balancing on different surfaces. The practitioners were provided with the results of the baseline tests to assist in the design of the rehabilitation program and were allowed to prescribe the program without interference from the research group. Upon completion of the intervention, all baseline tests were repeated. Importantly, the focus of the present study was on the use of various assessment *tools* (e.g., isokinetic dynamometer, force plates) and *metrics* (e.g., RSI, GCT, torque) in the evaluation of individuals with and without PFP and whether between-group differences can be detected using such approaches. Therefore, the study was designed to assess how effectively these tools and metrics can evaluate patient conditions, guide treatment decisions, and potentially predict rehabilitation outcomes. While rehabilitation is an essential component of patient care, its specific methodologies are not the primary variables under investigation. The individualized rehabilitation programs serve as a means to apply the insights gained from the assessment tools rather than being the subject of study themselves.

Ethics approval was granted by the Human Research Ethics Committee of the university and all ethical procedures conformed to the requirements of ethical conduct set forth in the Declaration of Helsinki.

2.5. Statistical Analyses

All statistical analyses were completed using R and JASP. The data were evaluated for normality using the Shapiro–Wilk test (*stats* package), whereby deviations from normality were accepted when $p < 0.05$. To appraise between-group differences as a function of time (pre vs. post intervention) and limb (injured/non-dominant vs. uninjured/dominant) for each of the kinetic and kinematic drop jump variables, a linear mixed effects model was used (*lme4* package), which also controlled for the potential effect of gender. Within this model, the independent variables accounted for the fixed effects and participants accounted for the random effect. Post hoc analyses were conducted (*emmeans* package) to evaluate within- and between-group differences where the Holm correction was implemented to adjust the *p*-values for multiple comparisons. Cohen's d (*effectsize* package) was calculated as the standardized effect size for each between-group comparison and was interpreted as follows: trivial: <0.2; small: 0.2–0.6; moderate: 0.6–1.2; and large: >1.2 [30].

To evaluate the diagnostic accuracy of jumping-based metrics, a binomial general linear model (*stats* package) and a receiver–operator characteristic (ROC) curve analysis (*ROCit* package) was conducted to evaluate the sensitivity and specificity of each metric [31]. The area under the curve (AUC) was used to compare metrics and was qualitatively interpreted as excellent ≥ 0.90; considerable: 0.80–0.90; fair: 0.70–0.79; and poor: <0.70 [32]. For each metric, the optimal cutoff point that maximises the sensitivity and specificity was calculated using Youden's index [33], which allows for the determination of the optimal threshold for each metric.

The associations between AKPS scores, jumping-based metrics and isometric strength were evaluated using a correlation analysis (*correlation* package). The magnitude of the correlation coefficients was qualitatively interpreted as follows: negligible: 0.00–0.10; weak: 0.10–0.39; moderate: 0.40–0.69; strong: 0.70–0.89; and very strong: 0.90–1.00 [34]. Statistical significance was accepted at $p \leq 0.05$.

3. Results

The anthropometric data of the participants are shown in Table 1.

Table 1. Anthropometric data of the participants (mean ± SD).

Variable	Pre Intervention		Post Intervention	
	Control	PFP	Control	PFP
Age (years)	22.13 ± 1.99	22.38 ± 3.07	22.13 ± 1.99	22.38 ± 3.07
Height (m)	1.73 ± 0.08	1.69 ± 0.08	1.72 ± 0.08	1.69 ± 0.08
Body mass (kg)	73.90 ± 16.36	74.37 ± 12.13	74.45 ± 15.99	74.44 ± 13.27

Note: PFP = patellofemoral pain group.

3.1. Kinetic and Kinematic Data

The results for between-group differences pertaining to unilateral peak force, jumping height, impulse, the RSI, and peak torque are shown in Figure 1. Once factors such as limb and gender were controlled for, statistically significant between-group differences were evident for GCT and the RSI but not for peak force, jumping height, or peak torque metrics.

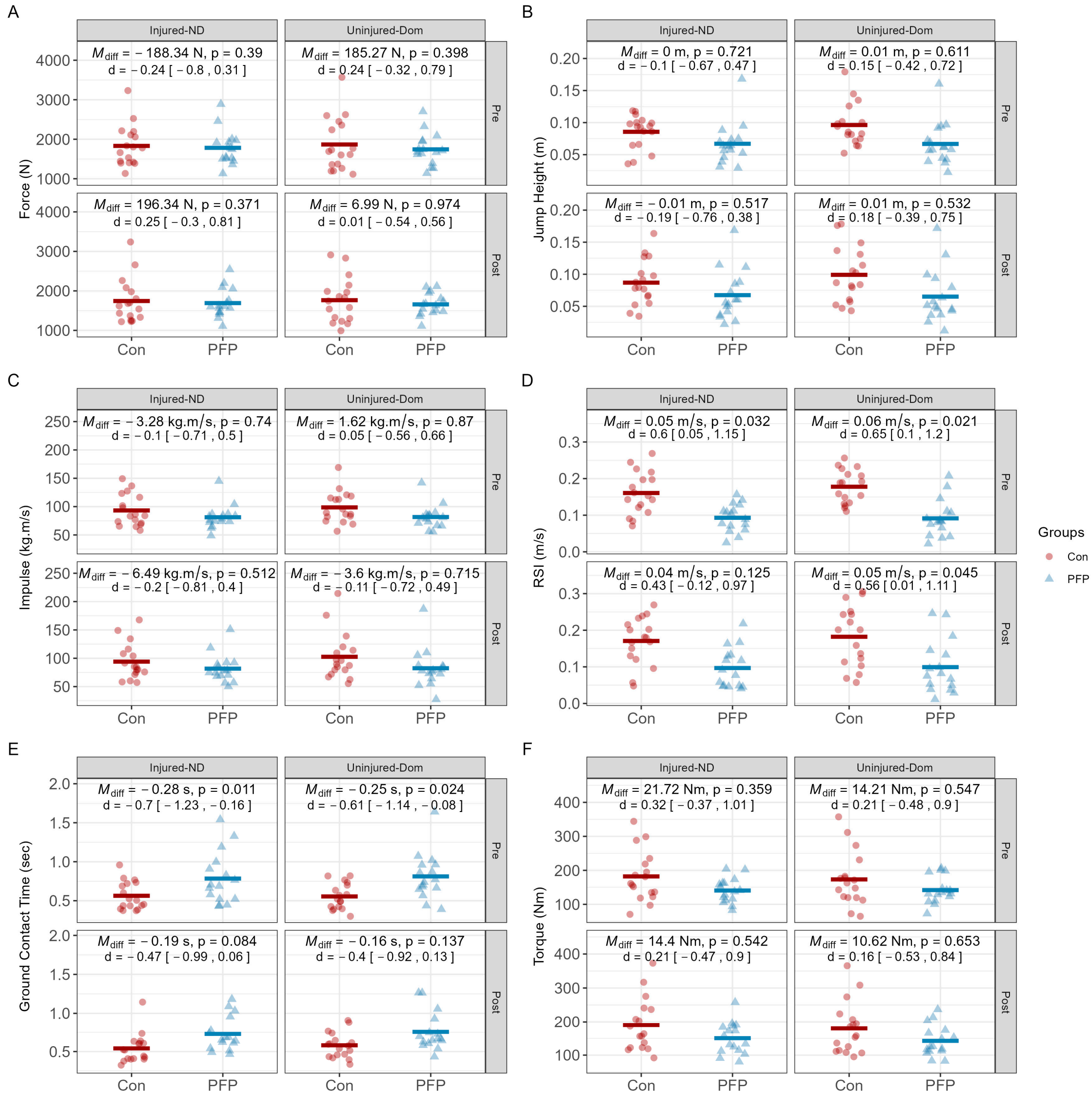

Figure 1. Non-parametric inferential results for between-group differences in kinetic and kinematic parameters. (**A**) shows peak force; (**B**) shows jump height; (**C**) shows the jump impulse; (**D**) shows the reactive strength index (RSI); (**E**) shows the ground contact time; (**F**) shows the peak isometric torque. Note: M_{diff} = median difference; ND = non-dominant limb; Dom = dominant limb; Con = control group; PFP = patellofemoral pain group; RSI = reactive strength index; horizontal bars indicate the median value for each metric; d = Cohen's d with a 95% confidence interval.

3.2. Diagnostic Accuracy

The results for the diagnostic accuracy and cutoff thresholds for key jumping-based metrics are shown in Figure 2. Importantly, gender was controlled for as a potential confounder in the logistic regression analysis to focus on the fundamental between-group differences. The coefficients for each term in the logistic regression equations are provided in the Supplementary Materials, which practitioners can use to enhance their decision making.

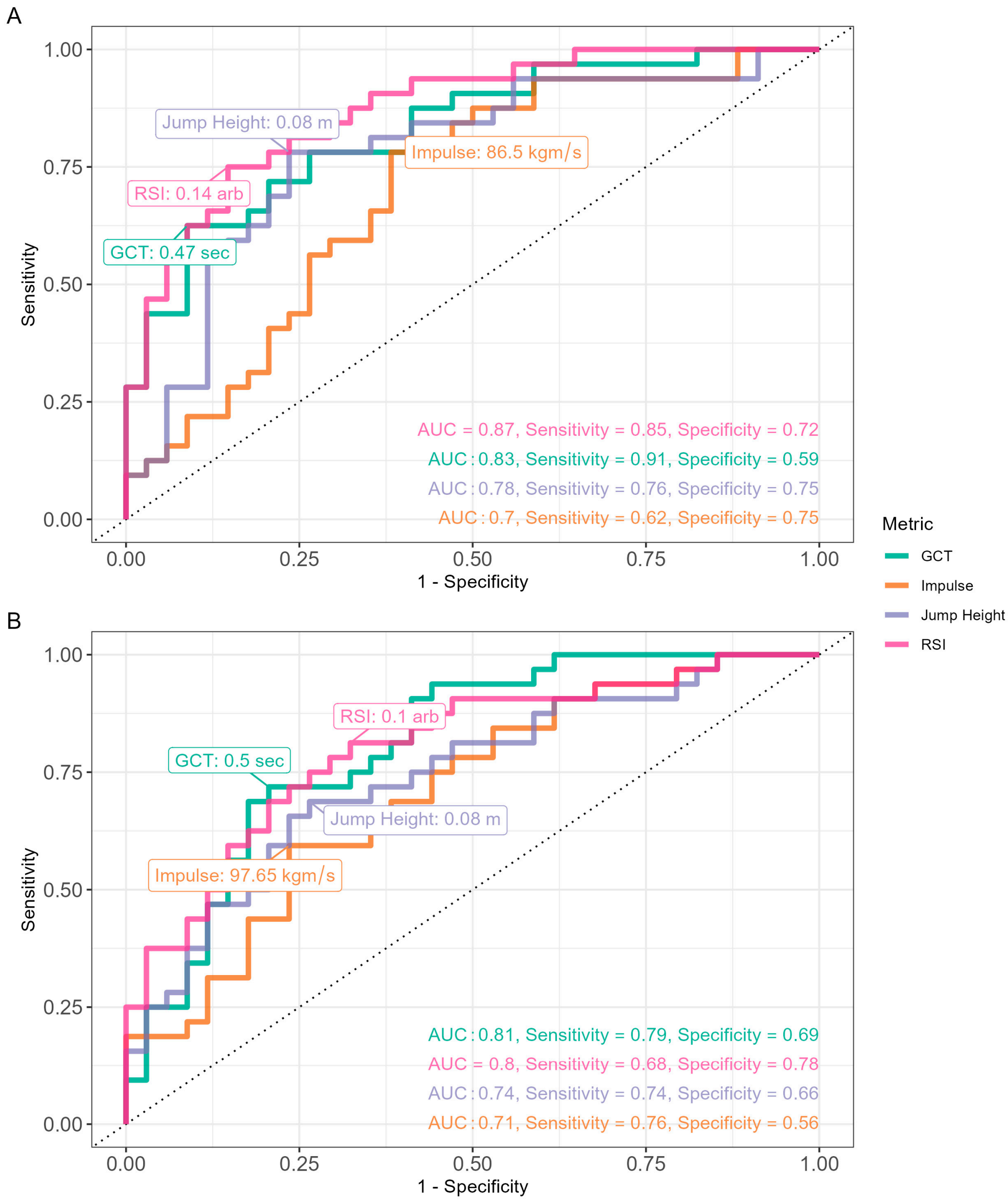

Figure 2. Receiver–operator characteristic (ROC) curve results for RSI, jump height, and jump momentum. (**A**) shows the pre-intervention results; (**B**) shows the post-intervention results. The optimal threshold for each metric is shown for reference. Note: AUC = area under the curve; RSI = reactive strength index; GCT = ground contact time.

Both baseline and post-intervention performances indicate that the RSI and GCT metrics have considerable diagnostic utility for differentiating PFP from healthy performances (AUC > 0.80) [28]. Jumping height and impulse seem to show adequate utility (AUC: 0.70–0.80).

3.3. Associations with the Anterior Knee Pain Scale

The results for the associations between AKPS scores and both kinetic and kinematic parameters are presented in Figure 3, where the associations are ranked from highest to lowest based on the absolute magnitude of the correlation coefficient.

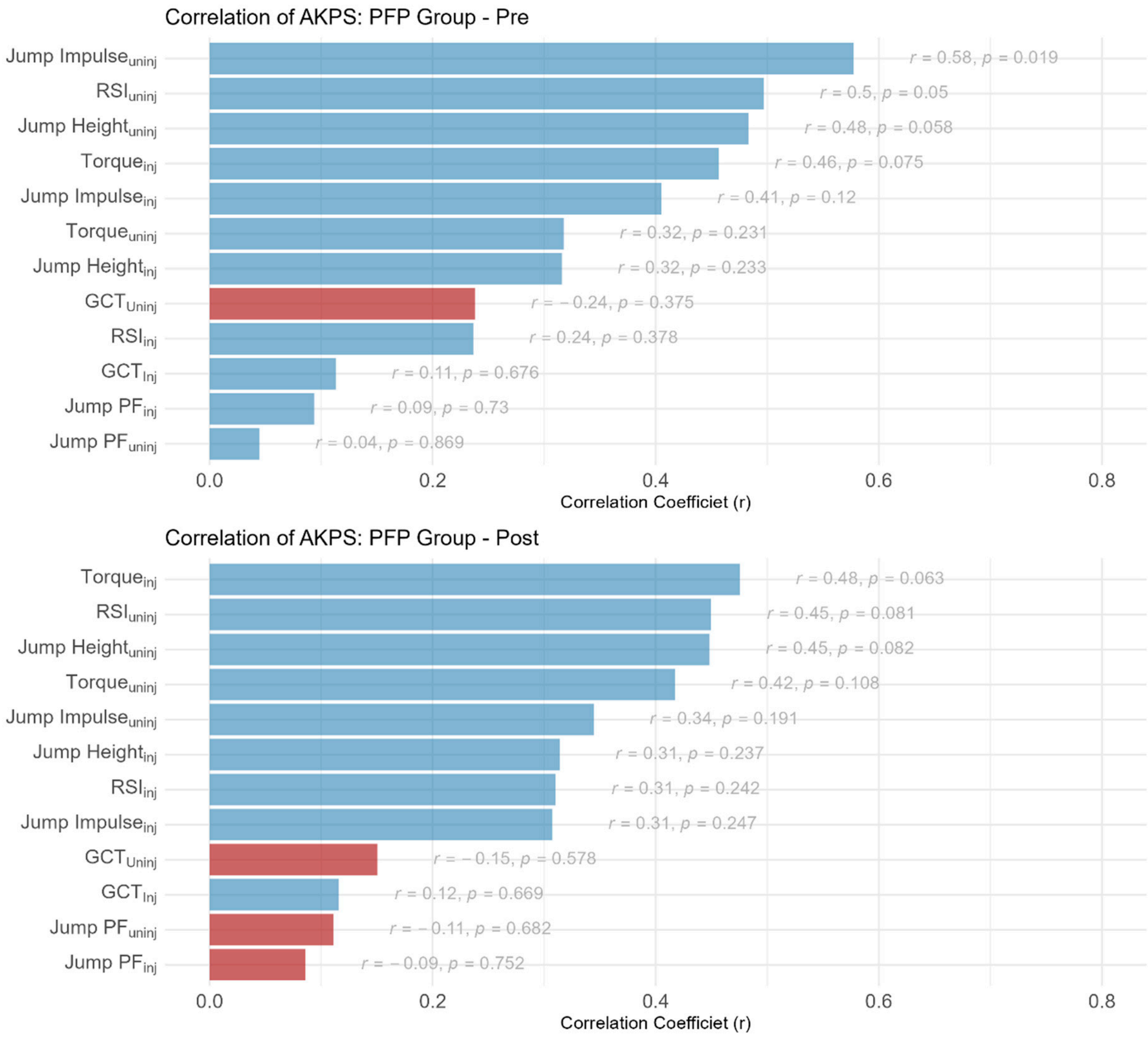

Figure 3. Correlation results between kinetic and kinematic parameters and the AKPS for the PFP group. Top panel shows the correlations between metrics prior to the intervention; bottom panel shows the correlations between post-intervention metrics. Note: PFP = patellofemoral pain; AKPS = anterior knee pain scale; inj = injured limb; uninj = uninjured limb; RSI = reactive strength index; GCT = ground contact time; blue bars indicates positive correlation; red bars indicate negative correlations.

At baseline, moderate associations are evident between the AKPS score and jumping based metrics, specifically impulse and the RSI. Following the intervention, isometric knee extensor torque and the RSI show the largest associations.

4. Discussion

The present study revealed the following novel findings. Firstly, an analysis of the kinetic and kinematic parameters showed that significant between-group differences were evident for unilateral jumping-based metrics such as the RSI, and GCT. Secondly, we established that the RSI and GCT metrics derived from unilateral drop jumping show promise as potential *diagnostic* metrics for identifying participants that may exhibit PFP. Finally, we indicated that the AKPS score (a subjective measure of pain) was moderately associated with the RSI and impulse scores (objective measures of performance), accounting for approximately 25–34% of the variability in performance.

4.1. Kinetic and Kinematic Data

The jumping-based metrics used in the present study (e.g., the RSI, GCT, impulse, jumping height) were chosen on the basis that they exhibited high levels of consistency, thereby making them ideal candidates for evaluating jumping-based performances [12]. Statistically significant between-group differences were evident for the unilateral jumping RSI and GCT, especially for the injured/non-dominant limbs. Evidence has shown that knee extensor muscle strength can be compromised in the uninjured limb following knee injury [35] and that muscle strength is associated with RSI performances during unilateral DJ performances [36]. Intriguingly, no statistically significant differences were evident for peak isometric torque between groups, which highlights the importance of incorporating functionally relevant tests as these may invoke greater overall contributions from the knee joint. Similarly, there was a lack of evidence for between-group differences regarding unilateral jumping impulse or peak ground reaction force in the present study, which likely implies similar motor coordination strategies during the take-off phase [37]. Our results echoed the findings from other studies that implemented unilateral jumping [38] and stair descent [39] but contradicted those by Nunes et al. [40], who showed 11% greater peak vertical GRF in individuals with PFP. It is plausible that methodological differences in the experimental setup may, at least partially, account for some of the differences given that Nunes et al. [40] used a 0.31 m box for their DJ trials, whereas we used a 0.25 m box. It is known that box height has a proportional effect on the magnitude of the ground reaction forces such that greater box heights elicit higher ground reaction forces [41].

The RSI metric, which comprised ground contact time (GCT) relative to flight time (a surrogate for jumping height), showed discernible between-group differences. Such a finding was intriguing given that disparities were evident for both the involved and uninvolved limbs compared to healthy controls. Accordingly, this result may indicate that the individuals in our sample might have employed a different motor control strategy during the initial landing and subsequent take-off, which is reliant on the stretch-shortening cycle and is known to be different in those with functional knee deficits [40,42]. More specifically, the lower RSI values of the PFP group can largely be explained by the longer contact duration during the initial landing (i.e., CGT) which may indicate a compensation strategy to minimise the vertical impulse generation to reduce knee loading [11] and correlates with the finding that people with PFP have lower rates of the force development of the muscles around the knee [43]. Although the RSI has been identified as a better marker of rehabilitation progression in those with ACL reconstruction [42,44], to the best of our knowledge, there are no previous studies reporting RSI in people with PFP, especially in terms of its potential value as a diagnostic metric. Studies focusing on the diagnostic accuracy of various clinical tests used to assess PFP showed that functional tests such as squatting, stair climbing and kneeling exhibited the highest sensitivity (0.84–0.91) but demonstrated limited specificity (0.43–0.50) [7,45]. Our study provides partial evidence that the RSI may serve as a potential diagnostic metric when evaluating those with PFP as part of a comprehensive testing battery given its sensitivity (0.85) and specificity (0.72). Moreover, GCT could also serve as potential surrogate given that its sensitivity (0.91) and specificity (0.59) scores tend to outweigh the majority of other functional diagnostic markers typically used in the evaluation of PFP patients (e.g., pain during stair climbing, pain during kneeling) (see Figure 2) [8]. Importantly, the metrics provided in the present study can be easily derived using force plates, the costs of which have dropped considerably in recent years, which means that such technologies are no longer the sole domain of specialist institutions. Although not evaluated in the present study, advances in cell phone technologies and the development of applications, such as MyJump2, means that metrics such as jumping height, GCT, and the RSI can be reliably and validly obtained without access to force plates, thereby increasing the adoption of such testing in clinical practice [46–48].

4.2. Associations with AKPS

The AKPS is a qualitative tool used to capture the perception of pain in those with PFP [49]. Intriguingly, within the PFP group, the AKPS score demonstrated a moderate positive correlation with the impulse (r = 0.58) and RSI (r = 0.50) values associated with the uninjured limbs, whereby approximately 25–34% of the variability in performance could be explained by the AKPS scores alone. More importantly, this indicates that key jumping-based metrics could be well suited to identify dynamic deficits in people with PFP as it may capture the motor control hesitancy of this group during dynamic jumping tasks. A recent systematic review found that RSI relates to improved performance in physical capacities and sport performance tasks, yet its utility across different injuries is under-researched [50]. Isometric strength in the injured limb was also moderately correlated with the AKPS (r = 0.46), implying that 21% of the variability in strength can be explained by the qualitative perceptions of pain captured by the AKPS score. Other studies on different performance variables such as sit to stand, trunk side flexion, and hip mobility also found similar correlations with the AKPS [51]. Therefore, the AKPS can account for a meaningful portion of the performance in objective performance measures and can be used to help with tracking progress in the rehabilitation of PFP. Stated differently, a psychological measure of pain, such as the AKPS score, appears to capture dynamic task variability where pain apprehension may be a limiting factor in task performance. Importantly, the simplicity of both the experimental setup and completion of the AKPS would allow for the more frequent monitoring of the rehabilitation process, which in turn would facilitate more appropriate decision-making processes. Some research has shown that exercise selection for the treatment of PFP is often too simplistic or lacks the appropriate progression for exercise-based therapy to be effective [52]. As such, more regular monitoring could guide practitioners to more valuable and/or appropriate exercise selection based on the performance outcomes.

Although there were several benefits connected with this study, there were also a few limitations. Participants did not follow a standardised rehabilitation program as they came from different clinical practices and were therefore subject to the guidelines implemented by their resident practitioner. Future studies may control the specific intervention program to determine their effect on the measured parameters. However, by demonstrating the utility of force plates (and the metrics derived from them) across various individualized programs, the present study provides broad applicability and supports the tools' relevance in different clinical contexts. Further, the ratio of males versus females differed between the control and PFP groups, although no other anthropometric differences were apparent. We used force plates to evaluate kinetic and kinematic parameters, which may not necessarily be accessible to practitioners. Therefore, although alternative lower-cost technologies (e.g., MyJump2) can provide similar metrics, it is unclear whether these tools can exhibit similar diagnostic insights, therefore providing an avenue for future research.

5. Conclusions

The aim of this study was to evaluate between-group differences for force plate-derived kinetic and kinematic variables, establish whether diagnostic thresholds could be determined, and investigate the association of AKPS scores with kinetic and kinematic parameters in those with PFP. We found meaningful between-group differences in jump height, the RSI, and GCT, implying that people with PFP have a reduced ability to quickly transition from eccentric deceleration to concentric acceleration compared to their non-PFP counterparts. The RSI especially may serve as a diagnostic metric in the evaluation of PFP patients. Lastly, the AKPS was shown to have a moderate positive correlation with the RSI, impulse, and isometric quadriceps strength in people with PFP, with approximately 21–34% of the variability in the AKPS score being attributed to these variables, making the AKPS a viable instrument to use in determining functional performance readiness and tracking rehabilitation progress in people with PFP.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app142311058/s1, Equations S1: Conversion Equations.

Author Contributions: The author contributions were as follows: conceptualization, G.D. and M.K.; methodology, G.D. and M.K.; formal analysis, M.K.; investigation, G.D. and M.K.; data curation, G.D.; writing—original draft preparation, G.D., M.K. and M.v.A.; writing—review and editing, G.D., M.K. and M.v.A.; visualization, M.K.; supervision, M.K. and M.v.A.; project administration, G.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Human Research Ethics Committee (HREC) of North-West University (NWU-00163-22-A1, 20 November 2022).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the patient(s) to publish this paper.

Data Availability Statement: The data supporting the reported results can be accessed from the Harvard Dataverse: https://doi.org/10.7910/DVN/NZH31Y.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Witvrouw, E.; Lysens, R.; Bellemans, J.; Cambier, D.; Vanderstraeten, G. Intrinsic Risk Factors for the Development of Anterior Knee Pain in an Athletic Population: A Two-Year Prospective Study. *Am. J. Sports Med.* **2000**, *28*, 480–489. [CrossRef] [PubMed]
2. Dye, S.F. The Pathophysiology of Patellofemoral Pain: A Tissue Homeostasis Perspective. *Clin. Orthop. Relat. Res.* **2005**, *436*, 100–110. [CrossRef] [PubMed]
3. Taunton, J.E.; Ryan, M.B.; Clement, D.B.; McKenzie, D.C.; Lloyd-Smith, D.R.; Zumbo, B.D. A Retrospective Case-Control Analysis of 2002 Running Injuries. *Br. J. Sports Med.* **2002**, *36*, 95–101. [CrossRef] [PubMed]
4. Kasitinon, D.; Li, W.-X.; Wang, E.X.S.; Fredericson, M. Physical Examination and Patellofemoral Pain Syndrome: An Updated Review. *Curr. Rev. Musculoskelet. Med.* **2021**, *14*, 406–412. [CrossRef] [PubMed]
5. Wood, L.; Muller, S.; Peat, G. The Epidemiology of Patellofemoral Disorders in Adulthood: A Review of Routine General Practice Morbidity Recording. *Prim. Health Care Res. Dev.* **2011**, *12*, 157–164. [CrossRef]
6. Papadopoulos, K.; Noyes, J.; Jones, J.G.; Thom, J.M.; Stasinopoulos, D. Clinical Tests for Differentiating between Patients with and without Patellofemoral Pain Syndrome. *Hong Kong Physiother. J.* **2014**, *32*, 35–43. [CrossRef]
7. Nunes, G.S.; Stapait, E.L.; Kirsten, M.H.; de Noronha, M.; Santos, G.M. Clinical Test for Diagnosis of Patellofemoral Pain Syndrome: Systematic Review with Meta-Analysis. *Phys. Ther. Sport* **2013**, *14*, 54–59. [CrossRef]
8. Cook, C.; Mabry, L.; Reiman, M.P.; Hegedus, E.J. Best Tests/Clinical Findings for Screening and Diagnosis of Patellofemoral Pain Syndrome: A Systematic Review. *Physiotherapy* **2012**, *98*, 93–100. [CrossRef]
9. Song, K.; Scattone Silva, R.; Hullfish, T.J.; Silbernagel, K.G.; Baxter, J.R. Patellofemoral Joint Loading Progression Across 35 Weightbearing Rehabilitation Exercises and Activities of Daily Living. *Am. J. Sports Med.* **2023**, *51*, 2110–2119. [CrossRef]
10. Hart, H.F.; Patterson, B.E.; Crossley, K.M.; Culvenor, A.G.; Khan, M.C.M.; King, M.G.; Sritharan, P. May the Force Be with You: Understanding How Patellofemoral Joint Reaction Force Compares across Different Activities and Physical Interventions—A Systematic Review and Meta-Analysis. *Br. J. Sports Med.* **2022**, *56*, 521–530. [CrossRef]
11. Liew, B.X.W.; Rugamer, D.; Abichandani, D.; De Nunzio, A.M. Classifying Individuals with and without Patellofemoral Pain Syndrome Using Ground Force Profiles-Development of a Method Using Functional Data Boosting. *Gait Posture* **2020**, *80*, 90–95. [CrossRef] [PubMed]
12. Celik, H.; Yildirim, A.; Unver, E.; Mavili, C.; Yilmaz, E.; Ozturk, F.; Arpinar-Avsar, P.; Alpan Cinemre, S. Force-Time Analysis of the Drop Jump: Reliability of Jump Measures and Calculation Methods for Measuring Jump Height. *Meas. Phys. Educ. Exerc. Sci.* **2024**, *28*, 119–132. [CrossRef]
13. Reijnders, L.; Van de Groes, S.A.W. The Quality of Life of Patients with Patellofemoral Pain—A Systematic Review. *Acta Orthop. Belg.* **2020**, *86*, 678–687.
14. Collins, N.J.; Bierma-Zeinstra, S.M.A.; Crossley, K.M.; Van Linschoten, R.L.; Vicenzino, B.; Van Middelkoop, M. Prognostic Factors for Patellofemoral Pain: A Multicentre Observational Analysis. *Br. J. Sports Med.* **2013**, *47*, 227–233. [CrossRef]
15. Thomas, M.J.; Wood, L.; Selfe, J.; Peat, G. Anterior Knee Pain in Younger Adults as a Precursor to Subsequent Patellofemoral Osteoarthritis: A Systematic Review. *BMC Musculoskelet. Disord.* **2010**, *11*, 201. [CrossRef]
16. Tan, S.S.; Van Linschoten, R.L.; Van Middelkoop, M.; Koes, B.W.; Bierma-Zeinstra, S.M.; Koopmanschap, M.A. Cost-utility of Exercise Therapy in Adolescents and Young Adults Suffering from the Patellofemoral Pain Syndrome. *Scand. Med. Sci. Sports* **2010**, *20*, 568–579. [CrossRef]
17. Howe, T.E.; Dawson, L.J.; Syme, G.; Duncan, L.; Reid, J. Systematic Review Evaluation of Outcome Measures for Use in Clinical Practice for Adults with Musculoskeletal Conditions of the Knee: A Systematic Review. *Man. Ther.* **2012**, *17*, 100–118. [CrossRef]

18. Christensen, L.B.; Johnson, R.B.; Turner, L.A. *Research Methods, Design and Analysis*; Pearson Education Limited: Harlow, UK, 2015; ISBN 978-0-205-96125-2.
19. Faul, F.; Erdfelder, E.; Lang, A.-G.; Buchner, A. G*Power 3: A Flexible Statistical Power Analysis Program for the Social, Behavioral, and Biomedical Sciences. *Behav. Res. Methods* **2007**, *39*, 175–191. [CrossRef]
20. Xu, J.; Jordan, M.J.; Chavda, S.; Turner, A.; Bishop, C. Test–Retest Reliability of the Magnitude and Direction of Asymmetry in the Countermovement Jump, Drop Jump, and Countermovement Rebound Jump. *Symmetry* **2023**, *15*, 1960. [CrossRef]
21. Watson, C.J.; Propps, M.; Ratner, J.; Zeigler, D.L.; Horton, P.; Smith, S.S. Reliability and Responsiveness of the Lower Extremity Functional Scale and the Anterior Knee Pain Scale in Patients with Anterior Knee Pain. *J. Orthop. Sports Phys. Ther.* **2005**, *35*, 136–146. [CrossRef]
22. Rahmati, M.; Gondin, J.; Malakoutinia, F. Effects of Neuromuscular Electrical Stimulation on Quadriceps Muscle Strength and Mass in Healthy Young and Older Adults: A Scoping Review. *Phys. Ther.* **2021**, *101*, pzab144. [CrossRef] [PubMed]
23. Foster, C.; Florhaug, J.A.; Franklin, J.; Gottschall, L.; Hrovatin, L.A.; Parker, S.; Doleshal, P.; Dodge, C. A New Approach to Monitoring Exercise Training. *J. Strength Cond. Res.* **2001**, *15*, 109–115. [PubMed]
24. Karcioglu, O.; Topacoglu, H.; Dikme, O.; Dikme, O. A Systematic Review of the Pain Scales in Adults: Which to Use? *Am. J. Emerg. Med.* **2018**, *36*, 707–714. [CrossRef] [PubMed]
25. Ortiz, A.; Olson, S.; Libby, C.L.; Kwon, Y.-H.; Trudelle-Jackson, E. Kinematic and Kinetic Reliability of Two Jumping and Landing Physical Performance Tasks in Young Adult Women. *North Am. J. Sports Phys. Ther. NAJSPT* **2007**, *2*, 104–112.
26. Wang, L.I.; Peng, H.T. Biomechanical Comparisons of Single- and Double-Legged Drop Jumps with Changes in Drop Height. *Int. J. Sports Med.* **2014**, *35*, 522–527. [CrossRef]
27. Barker, L.; Bankers, S.; Farmer, B.; Siedlik, J.; Harry, J.; Grindstaff, T.L. The Influence of Verbal Cues on Drop Jump Landing Strategies in NCAA Division I Soccer Players. *AJSS* **2021**, *9*, 37. [CrossRef]
28. Grozier, C.D.; Cagle, G.K.; Pantone, L.; Rank, K.B.; Wilson, S.J.; Harry, J.R.; Seals, S.; Simpson, J.D. Effects of Medial Longitudinal Arch Flexibility on Propulsion Kinetics during Drop Vertical Jumps. *J. Biomech.* **2021**, *118*, 110322. [CrossRef]
29. Xu, J.; Turner, A.; Comfort, P.; Harry, J.R.; McMahon, J.J.; Chavda, S.; Bishop, C. A Systematic Review of the Different Calculation Methods for Measuring Jump Height During the Countermovement and Drop Jump Tests. *Sports Med.* **2023**, *53*, 1055–1072. [CrossRef]
30. Hopkins, W.G.; Marshall, S.W.; Batterham, A.M.; Hanin, J. Progressive Statistics for Studies in Sports Medicine and Exercise Science. *Med. Sci. Sports Exerc.* **2009**, *41*, 3–12. [CrossRef]
31. Corbacioglu, Ş.; Aksel, G. Receiver Operating Characteristic Curve Analysis in Diagnostic Accuracy Studies: A Guide to Interpreting the Area under the Curve Value. *Turk. J. Emerg. Med.* **2023**, *23*, 195. [CrossRef]
32. Mandrekar, J.N. Receiver Operating Characteristic Curve in Diagnostic Test Assessment. *J. Thorac. Oncol.* **2010**, *5*, 1315–1316. [CrossRef]
33. Nahm, F.S. Receiver Operating Characteristic Curve: Overview and Practical Use for Clinicians. *Korean J. Anesth.* **2022**, *75*, 25–36. [CrossRef] [PubMed]
34. Schober, P.; Schwarte, L.A. Correlation Coefficients: Appropriate Use and Interpretation. *Anesth. Analg.* **2018**, *126*, 1763–1768. [CrossRef] [PubMed]
35. Chung, K.S.; Ha, J.K.; Yeom, C.H.; Ra, H.J.; Lim, J.W.; Kwon, M.S.; Kim, J.G. Are Muscle Strength and Function of the Uninjured Lower Limb Weakened After Anterior Cruciate Ligament Injury?: Two-Year Follow-up After Reconstruction. *Am. J. Sports Med.* **2015**, *43*, 3013–3021. [CrossRef] [PubMed]
36. Crotty, N.M.N.; Daniels, K.A.J.; McFadden, C.; Cafferkey, N.; King, E. Relationship Between Isokinetic Knee Strength and Single-Leg Drop Jump Performance 9 Months After ACL Reconstruction. *Orthop. J. Sports Med.* **2022**, *10*, 23259671211063800. [CrossRef]
37. Liew, B.X.W.; Abichandani, D.; De Nunzio, A.M. Individuals with Patellofemoral Pain Syndrome Have Altered Inter-Leg Force Coordination. *Gait Posture* **2020**, *79*, 65–70. [CrossRef]
38. Willson, J.D.; Davis, I.S. Lower Extremity Strength and Mechanics during Jumping in Women with Patellofemoral Pain. *J. Sport Rehabil.* **2009**, *18*, 76–90. [CrossRef]
39. Saad, M.C.; Moraes, R.; Felicio, L.R.; Bevilaqua-Grossi, D. Braking and Propulsive Impulses in Individuals with Patellofemoral Pain Syndrome When Walking up and down Stairs. *Motriz. Rev. Educ. Fisica* **2014**, *20*, 442–447. [CrossRef]
40. Nunes, G.S.; Barton, C.J.; Viadanna Serrão, F. Females with Patellofemoral Pain Have Impaired Impact Absorption during a Single-Legged Drop Vertical Jump. *Gait Posture* **2019**, *68*, 346–351. [CrossRef]
41. Makaruk, H.; Sacewicz, T. The Effect of Drop Height and Body Mass on Drop Jump Intensity. *Biol. Sport* **2011**, *28*, 63–67. [CrossRef]
42. Kotsifaki, A.; Van Rossom, S.; Whiteley, R.; Korakakis, V.; Bahr, R.; Sideris, V.; Jonkers, I. Single Leg Vertical Jump Performance Identifies Knee Function Deficits at Return to Sport after ACL Reconstruction in Male Athletes. *Br. J. Sports Med.* **2022**, *56*, 490–498. [CrossRef] [PubMed]
43. Nunes, G.S.; Barton, C.J.; Serrão, F.V. Impaired Knee Muscle Capacity Is Correlated with Impaired Sagittal Kinematics During Jump Landing in Women with Patellofemoral Pain. *J. Strength Cond. Res.* **2022**, *36*, 1264–1270. [CrossRef] [PubMed]
44. Read, P.J.; Davies, W.T.; Bishop, C.; McAuliffe, S.; Wilson, M.G.; Turner, A.N. Residual Deficits in Reactive Strength After Anterior Cruciate Ligament Reconstruction in Soccer Players. *J. Athl. Train.* **2023**, *58*, 423–429. [CrossRef] [PubMed]

45. Cook, C.; Hegedus, E.; Hawkins, R.; Scovell, F.; Wyland, D. Diagnostic Accuracy and Association to Disability of Clinical Test Findings Associated with Patellofemoral Pain Syndrome. *Physiother. Can.* **2010**, *62*, 17–24. [CrossRef]
46. Whiteley, I.; Sideris, V.; Kotsifaki, R.; King, E.; Whiteley, R. The MyJump App Is a Valid Method of Assessing and Classifying Limb Symmetry During Recovery from Anterior Cruciate Ligament Reconstruction. *Int. J. Sports Phys. Ther.* **2023**, *18*, 1156–1165. [CrossRef]
47. Pueo, B.; Hopkins, W.; Penichet-Tomas, A.; Jimenez-Olmedo, J. Accuracy of Flight Time and Countermovement-Jump Height Estimated from Videos at Different Frame Rates with MyJump. *Biol. Sport* **2023**, *40*, 595–601. [CrossRef] [PubMed]
48. Haynes, T.; Bishop, C.; Antrobus, M.; Brazier, J. The Validity and Reliability of the My Jump 2 App for Measuring the Reactive Strength Index and Drop Jump Performance. *J. Sports Med. Phys. Fit.* **2019**, *59*, 253–258. [CrossRef]
49. Ittenbach, R.F.; Huang, G.; Foss, K.D.B.; Hewett, T.E.; Myer, G.D. Reliability and Validity of the Anterior Knee Pain Scale: Applications for Use as an Epidemiologic Screener. *PLoS ONE* **2016**, *11*, e0159204. [CrossRef] [PubMed]
50. Jarvis, P.; Turner, A.; Read, P.; Bishop, C. Reactive Strength Index and Its Associations with Measures of Physical and Sports Performance: A Systematic Review with Meta-Analysis. *Sports Med.* **2022**, *52*, 301–330. [CrossRef]
51. Zamboti, C.L.; Marçal Camillo, C.A.; Ricardo Rodrigues Da Cunha, A.P.; Ferreira, T.M.; Macedo, C.S.G. Impaired Performance of Women with Patellofemoral Pain during Functional Tests. *Braz. J. Phys. Ther.* **2021**, *25*, 156–161. [CrossRef]
52. Dischiavi, S.L.; Wright, A.A.; Tarara, D.T.; Bleakley, C.M. Do Exercises for Patellofemoral Pain Reflect Common Injury Mechanisms? A Systematic Review. *J. Sci. Med. Sport* **2021**, *24*, 229–240. [CrossRef]