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# Curves and kinematics: Relationship between the force-time curve and landing ability

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Anterior cruciate ligament (ACL) injuries have a significant impact on athletic performance and long-term quality of life. Force plates and qualitative screening tools are feasible and effective screening methods to identify abnormal movement quality associated with increased injury risk. Comparing qualitative assessments of landing ability with force-time curves, may detect unique differences between safe and high-risk athletic movement patterns. The aim of this study was to determine low- and high-risk landing ability from qualitive landing assessments and to examine the resulting force-time curves using functional principal component analysis (fPCA). Thirty-one healthy academy athletes (10 males and 21 females) completed double- and single-leg dominant and non-dominant jump-landing-rebound tasks. All movements were filmed in multiple-planes, and vertical ground reaction forces (vGRF) were simultaneously collected. The Landing Error Scoring System (LESS) and Single-Leg Landing Error Scoring System (SL-LESS) were used to score landing footage. From these scores, athletes were categorized into low-risk and high-risk groups for further analysis. fPCA was used to examine differences between landing quality groups force-time curves. Compared to high-risk landers, low-risk landers demonstrated significantly longer contact times across all movements. Scores from fPC1 revealed safe and high-risk landing techniques expose athletes to significantly different loading patterns during double- and single-leg dominant movements. A significant positive relationship was observed between fPC1 and LESS scores, however this relationship was not observed in both single-leg landing scores. Where possible incorporating curve analysis methods like fPCA into multi-faceted screening approaches may help practitioners uncover unique insights into athletic loading strategies.

KEYWORDS

curve analysis, force, landing, qualitative assessment, screening

## 1 | INTRODUCTION

Research has identified that anterior cruciate ligament (ACL) injuries occur most frequently in a young, active population (<25 years of age) who participate in multidirectional team sports.[1,2] Team sports movement patterns are characterized by frequent rapid decelerations such as landing from a jump and changing direction. These movements, expose the knee joint to large moments which excessively load the ACL and can result in injury.[3] Although exposure to these non-contact movements is unavoidable, prior research has indicated that those at a greater risk of ACL injury demonstrate particular lower limb mechanics including dynamic knee valgus[4] and an extended knee position.[5] Identifying athletes who may be at an increased risk of ACL injury via observation of their mechanics in a controlled setting, is an important strategy to help guide interventions that may reduce the risk of potential injury.[6] This early identification strategy may help mitigate the negative impact ACL injuries have on athletic performance[7] and long-term quality of life.[2]

Screening methods that assess modifiable neuromuscular and biomechanical risk factors are thought to be effective tools for identifying athletes who may be at an increased risk of injury.[8] The effectiveness of these methods relies on their ability to identify risk factors associated with injury during movements where injuries typically occur.[9] Whilst ACL injuries frequently occur during sidestep cutting and landing tasks,[10] previous literature has predominantly utilized valid and reliable landing tasks to investigate mechanisms of ACL injury.[4,5,11] However, the gold standard movement analysis method (3D motion analysis) used in most of these pioneering studies is not a feasible screening option for most clinical and sporting settings, thus further complicating how injury risk is determined.[8] Field-based screening tools such as the Landing Error Scoring System (LESS),[12] and the Single-Leg Landing Error Scoring System (SL-LESS)[13] have been developed to provide a cost-effective and easily implementable alternative, enabling the identification of abnormal movement patterns linked with an increased risk of lower extremity injury.[14] Despite field-based screening tools assessing the mechanisms of ACL injury, the predictive ability of the LESS is inconclusive,[15,16] and the SL-LESS has yet to be evaluated.[13] The complex nature of sports injuries means basing an indicator of injury risk on a single assessment may also be an over-simplificaton.[17] Therefore, incorporating objective measurements alongside subjective measurements such as the LESS may aid in further understanding at-risk athletic movement patterns.

The rising popularity of commercially available force plates has added an additional tool for practitioners to objectively evaluate athletic injury risk.[8] Force plates assess athletic movement capabilities using multiple directions of ground reaction forces (GRF) acting upon the body during sport-specific tasks.[18] Inadequate dissipation of GRF's is thought to excessively strain passive structures within the knee, thus increasing the likelihood of ACL injury.[19] Athletic injury risk is typically determined using discrete performance variables associated with ACL injury such as peak force or time to peak force.[4,5,20] Whilst valuable, this analysis method then ignores other aspects of the continuous force-time curve, which could potentially reveal information on technique. More sophisticated analytical approaches to overcome the limitations associated with discrete analysis[20–24] are being used more within sport science literature. Functional data analysis (FDA) has been used in recent landing and jumping research to identify variability from continuous kinetic and kinematic movement data.[20–24] Functional principal component analysis (fPCA) is one of the most common FDA techniques used to assess human movement.[21] Indeed, Stephens et al.[21] showed that by analyzing the entire continuous force-time data using fPCA, changes in an athlete's movement strategy post-ACL injury could be identified that were not evident when using discrete measures. Whilst PCA has been previously used by Ueno and colleges to model internal knee loading in cadavers.[25] The work of Stephens,[21] extends upon this, applying fPCA in an athlete monitoring context and additional research is needed to identify movement profiles of healthy athletes.

Therefore, the aim of this study was to determine bilateral low-risk and high-risk landing ability from qualitative landing assessments and to examine the corresponding force-time curves using fPCA. We hypothesize that as high-risk landing quality is associated with a greater number of landing errors hence potentially dangerous movement quality, high-risk landers will be exposed to greater forces (peak vGRF's), thus reflecting differences between low- and high-risk groups force-time curves throughout the landing cycle. A greater understanding of force-time curve characteristics associated with high-risk landing patterns will help practitioners identify athletes at an increased risk of injury, helping reduce the incidence of lower limb injuries and improving athletic landing capabilities.

## 2 | MATERIALS AND METHODS

### 2.1 | Participants

A total of 31 state-level athletes (11 males and 20 females) volunteered for this study (Table 1.) Sample size was calculated using G-Power 3.1.9.4 (Germany) comparing left and right force traces during landing.[5] Athletes meeting

**TABLE 1** Participant characteristics

| Jump landing task | Quality | *n* | Sex (M/F) | Age (Years) | Weight (kg) | Height (cm) |
|---|---|---|---|---|---|---|
| DL | Low risk | 9 | 6/3 | 20.7 ± 5.0 | 74.7 ± 6.9 | 179.0 ± 6.4 |
| | High risk | 22 | 5/17 | 19.9 ± 3.9 | 71.8 ± 11.0 | 177.1 ± 8.9 |
| SLD | Low risk | 11 | 3/8 | 20.7 ± 4.3 | 69.0 ± 10.4 | 173.2 ± 8.9 |
| | High risk | 20 | 8/12 | 19.8 ± 4.2 | 74.7 ± 9.4 | 180.1 ± 6.8 |
| SLND | Low risk | 19 | 10/9 | 20.0 ± 4.1 | 73.7 ± 9.1 | 179.5 ± 8.6 |
| | High risk | 12 | 1/11 | 20.3 ± 4.5 | 71.0 ± 11.5 | 174.8 ± 6.8 |
| Group | | 31 | 11/20 | 20.1 ± 4.1 | 72.6 ± 10.0 | 177.7 ± 8.2 |

Abbreviations: cm, centimeters; DL, double-leg; F, female; kg, kilograms; M, male; n, number; SLD, single-leg dominant; SLND, single-leg non-dominant.

this study's inclusion criteria were currently training in the Australian Capital Territory Academy of Sport (ACTAS) environment, participating in a team sport (field hockey, netball, rugby 7's, basketball, baseball, softball, and cricket) and cleared by a medical practitioner to participate in unrestricted physical activities. All participants were provided an information sheet outlining the study's requirements and completed informed consent and prescreening questionnaire documents prior to any involvement in this study to determine their eligibility. This study was approved by the University of Canberra review board which follows ethical guidelines set by the 1964 Helsinki Declaration.

## 2.2 | Testing procedures

All participants completed two sessions, a familiarization session, followed by a testing session completed 2–7 days later. Both session protocols were identical, except for anthropometric measurements of body mass, standing height and sitting height which were only collected during the familiarization session. All sessions took place in the ACTAS Strength and Conditioning Facility. Following this, a 10-min lower body warm-up consisting of a 3-min self-paced stationary cycle and specific bodyweight power and strength exercises (10 × body weighted squats, arabesque (each leg), pogo jumps and countermovement jumps at 50% and 75%) was completed. Following the warm-up, the primary investigator informed participants of the study requirements, followed by standardized verbal instructions and demonstrations of each jump-landing-rebound task. Specifically, participants were instructed to jump as high as they could once, they landed from the box and no additional feedback or coaching was provided unless they performed the landing task incorrectly.[12] Participants familiarized themselves with the jump-landing tasks by practicing as many attempts as needed to perform the task correctly.[12] Filmed footage of double-leg (DL) and single-leg dominant (SLD) and non-dominant (SLND) limb jump landing tasks, were recorded using tripod mounted iPad's (Apple, iPad Air 2, and iPad 6th Gen). Camera placement was standardized for all participants (see Figure S3). Participants were required to perform the landing tasks on a portable dual force plate (1000 Hz, 0.6 × 0.4 m, 9286BA, Kistler), which was zeroed (without applying any mass) prior to completing each jump landing trial. During testing, participants used their own athletic footwear which was standardized between all conditions.[26] Participants completed a total of nine successful jump landings, which equated to three successful trials for each jump landing task with 30 s rest between each trial.[27] A repeat trial was included if the participant failed to land on the plates at initial contact or if they deviated from the required landing technique, that is, did not stick landing.

## 2.3 | Double leg and single-leg jump landing tasks protocol

All jump-landing-rebound tasks were completed in a predetermined randomized order. Participants were allocated to one of six predetermined jump orders using a random number generator (Excel, Microsoft, USA). Jump tasks techniques were completed in accordance with prior research.[12,13] The DL task required participants to jump horizontally off a 30 cm-high box, positioned 50% of their standing height away from the landing marker located on the force plate, followed by a maximal vertical jump.[12] The SLD and SLND tasks required participants to jump horizontally off a 20 cm-high box, positioned 25% of their standing height away from the landing marker located on the force plate, followed by a maximal vertical jump on the same leg.[13]

To qualitatively determine low-risk and high-risk landers, protocols outlined in Padua et al.[12] and O'Connor 2015[13] were used to conduct DL, SLD, and SLND jump-landing-rebound jumping tasks, with the exception of instructing participants to place their hands on their hips throughout all movement tasks in order to mitigate arm swing contribution to landing and jumping performance.[28]

## 2.4 | Data processing

Qualitative scoring systems were used to determine movement quality from video footage. The LESS protocol designed by Padua et al.[12] was used to assess DL landings using 17 items associated with ACL injury risk. Single-leg landings were assessed using O′Connor's[13] modified version of the LESS (the SL-LESS) to assess single-leg landing quality using 11 items. Landing quality is determined by counting the total number of landing errors during key points in the landing sequence, scoring landing technique at initial contact and between initial contact and maximal knee flexion. A 0 or 1 scoring system is used for most items, with 1 indicating an error is present. Rater training was completed prior to scoring[15] and all jump landings were observed using a free computer software (Kinovea, Version 9.3). The mean score from three valid jumps was calculated,[26] and participants were categorized into "low-risk" and "high-risk" based on threshold scores. A cut score of >5 was used for the LESS,[29] and >3 used for the SL-LESS. Participant scores exceeding these predetermined cut-points were considered "high-risk" landers for the particular landing task and "low-risk" if they scored lower. GRF data were simultaneously collected from a portable dual force plate. Quantitative assessment of the jumps was assessed using the GRF's which were collected in anterior–posterior, medial-lateral, and vertical GRF (vGRF) directions along with the resultant vector force. Ground contact was defined as the point at which the vGRF trace exceeded 10 N, and take-off was identified as the time when vGRF was less than 10 N[12]. The vGRF's between initial ground contact and take off were retained and normalized to Newtons per kilogram (N/kg) for subsequent analysis using fPCA. Traditional performance measures peak vGRF ($vGRF_N$), contact time (sec), impulse (N/sec), and jump height (flight-time cm) were analyzed by ForceDecks software (Vald Performance, Force Decks Software Version, Brisbane, Queensland). Additional performance measures peak vGRF (N/kg) ($vGRF_{N/kg}$) and time to peak (sec) were also calculated from the original force time data. For each jump landing task, mean (quantitative) performance measures were calculated from three valid trials and used for further analyses.

## 2.5 | Data analysis

To assess inter-rater reliability, two experienced raters independently assessed (the same) 10 participants jump trials. Trials were randomly selected from all jump landing tasks and both raters were blinded to each other scores and intraclass correlation coefficient (ICC) was used to assess inter-rater reliability. To examine differences between landing quality groups, for each landing task participants qualitative landing score, and quantitative performance measures were divided into "low-risk" and "high-risk" quality groups, determined by the predetermined threshold scores, and averaged into two landing quality groups used for further analysis. An independent sample *t*-test set at an $\alpha$ level of $<0.05$ was used to determine differences between low-risk and high-risk landing quality groups qualitative landing scores and quantitative performance measures.

## 2.6 | vGRF time-series

To assess the force-time curves for each jump-landing-rebound tasks, participants force-time data from three trials were averaged and time normalized to 101 data points using an interpolating cubic spline. Participant waveforms were independently categorized into "low-risk" or "high-risk" landing quality, identified by the predetermined cut scores, and averaged into two landing quality curves used for subsequent analysis. Time normalized time-series data was used as inputs for FDA processes.[30,31] B-splines were used as a choice for function fitting, given their suitability with non-periodic (i.e., repetitive) data. A smoothing parameter was added as a part of the function fitting process and selected via generalized cross validation and subjective visual inspection of the fitted functions. No curve registration was performed and three separate fPCAs were conducted on the DL, and single-leg (dominant and non-dominant) trials independently. A full theoretical description of fPCA (and demonstrative software used to carry out this method) is available in Warmenhoven et al.[31] Additionally, a clinician and practitioner friendly description of the methods is also available in the Appendix 1. Derived functional principal component (fPC) scores, representing each original trial relative to characteristics displayed in each fPC, were compared statistically with LESS and SL-LESS scores using Pearson product moment correlations (with $\alpha$ set at 0.05). All data were analyzed using R (v3.6.2).

## 3 | RESULTS

### 3.1 | Qualitative screening scores & traditional performance measures

Landing quality descriptive data is presented as means ± standard deviations (SD), and significance ($p$-value) for LESS and SL-LESS scores, and traditional performance measures in Table 2. Inter-rater reliability was excellent, as ICC was 0.98.

Across all jump landing tasks, low-risk landers displayed significantly lower landing error scores compared to high-risk landers (Table 2). High-risk landers also displayed significantly less contact time in all jump landings tasks compared to low-risk landers. This increased contact time observed in low-risk DL and SLND landing groups resulted in substantially larger impulses compared with the high-risk landing groups. Furthermore, longer whole movement contact times did not translate to a longer time to peak vGRF for SLD and SLND jump landing tasks. However, low-risk DL landers were exposed to peak vGRF forces much sooner than high-risk landers. Low-risk landers jumped considerably higher after landing in the DL condition compared with high-risk landers. However, the opposite occurred in the SLD group, with high-risk landers jumping significantly higher and were exposed to significantly greater absolute and relative peak vGRF's than low-risk landers. Though, these differences in peak GRF's ($vGRF_N$ and $vGRF_{N/kg}$) between low-risk and high-risk groups were not observed during DL and SLND landings. The SLND landing group had a higher proportion of landers displaying low-risk landing technique (61%). Whereas both DL (71%) and SLD (65%) jump landing tasks had a higher number of high-risk landers.

### 3.2 | fPCA force-time assessment

A comparison of low-risk and high-risk landers fPC scores (mean ± SD) and significance ($p$-values) can be seen in Table 3.

A summary of between-group variation observed in fPC's one to three is displayed in Figure 1.

Across all fPCAs, fPCs identified consistent features. fPC1 identified differences in landing patterns from initial contact to the end of the concentric phase of the jump. fPC2 captured variation from initial contact to the peak $vGRF_{N/kg}$ phase of landing. fPC3 described curve variability from initial contact to the early stages of the breaking phase of landing. The first three fPC's for DL and SLND

TABLE 2 Jump landing task quality traditional performance measure summary

| Jump landing task | Quality | | Peak vGRF (N) | Peak vGRF (N/g) | Contact Time (sec) | Time to Peak vGRF (sec) | Whole Movement Impulse (N/sec) | Jump Height (FT cm) | LESS or SL-LESS | n |
|---|---|---|---|---|---|---|---|---|---|---|
| DL | Low risk | Mean ± SD | 3827.11 ± 1220.04 | 51.79 ± 17.43 | 0.47 ± 0.09 | 0.038 ± 0.012 | 1747.54 ± 464.31 | 29.60 ± 5.37 | 4.2 ± 0.9 | 9 |
| | High risk | Mean ± SD | 4038.44 ± 1497.96 | 55.86 ± 17.72 | 0.29 ± 0.06 | 0.051 ± 0.021 | 1131.62 ± 474.67 | 26.45 ± 4.14 | 7.8 ± 1.5 | 22 |
| | | *p*-Value | 0.482 | 0.314 | <0.001* | 0.008* | <0.001* | 0.009* | <0.001* | |
| SLD | Low risk | Mean ± SD | 2279.12 ± 304.71 | 33.36 ± 4.19 | 0.44 ± 0.13 | 0.054 ± 0.010 | 992.26 ± 292.34 | 12.06 ± 2.27 | 2.8 ± 0.3 | 11 |
| | High risk | Mean ± SD | 2748.25 ± 738.27 | 36.48 ± 7.35 | 0.38 ± 0.07 | 0.056 ± 0.026 | 1033.83 ± 308.04 | 13.74 ± 2.55 | 3.8 ± 0.5 | 20 |
| | | *p*-Value | <0.001* | 0.011* | 0.023* | 0.335 | 0.522 | 0.002* | <0.001* | |
| SLND | Low risk | Mean ± SD | 2556.70 ± 579.62 | 34.64 ± 6.21 | 0.45 ± 0.12 | 0.061 ± 0.024 | 1146.75 ± 349.44 | 12.77 ± 2.87 | 2.7 ± 0.3 | 19 |
| | High risk | Mean ± SD | 2494.03 ± 580.07 | 35.08 ± 5.29 | 0.34 ± 0.06 | 0.061 ± 0.015 | 826.91 ± 166.57 | 12.94 ± 1.72 | 3.8 ± 0.3 | 12 |
| | | *p*-Value | 0.613 | 0.712 | <0.001* | 0.618 | <0.001* | 0.720 | <0.001* | |

Abbreviations: DL, double-leg; F, female; FT cm, flight time in centimeters; LESS, landing error scoring system; M, male; N, Newtons; *n*, number; N/kg, Newtons per kilogram; N/sec, Newtons per second; sec, seconds; SLD, single-leg dominant; SL-LESS, single-leg landing error scoring system; SLND, single-leg non-dominant; vGRF, vertical ground reaction force.

*Indicates a $p$-value < 0.05 between low and high-risk landers.

**TABLE 3** Jump landing task quality functional principal component (fPC) summary

| Jump Landing Task | Quality | | fPC1 | fPC2 | fPC3 |
|---|---|---|---|---|---|
| DL | Low risk | Mean ± SD | −66.97 ± 26.44 | −16.06 ± 31.01 | 7.43 ± 12.52 |
| | High risk | Mean ± SD | 27.40 ± 64.10 | 6.57 ± 24.29 | −3.04 ± 14.28 |
| | | *p*-Value | <0.001* | 0.073 | 0.058 |
| SLD | Low risk | Mean ± SD | −10.46 ± 40.09 | −3.42 ± 13.38 | 0.817 ± 8.30 |
| | High risk | Mean ± SD | 5.75 ± 31.20 | 1.88 ± 15.30 | −0.45 ± 9.23 |
| | | *p*-Value | 0.262 | 0.327 | 0.700 |
| SLND | Low risk | Mean ± SD | −17.47 ± 35.52 | 0.46 ± 16.10 | 1.77 ± 8.39 |
| | High risk | Mean ± SD | 27.66 ± 30.10 | −0.73 ± 9.07 | −2.80 ± 9.30 |
| | | *p*-Value | <0.001* | 0.795 | 0.180 |

Abbreviations: DL, double-leg; fPC, functional principal component; SLD, single-leg dominant; SLND, single-leg non-dominant.
*Indicates a *p*-value < 0.05 between low and high-risk landers.

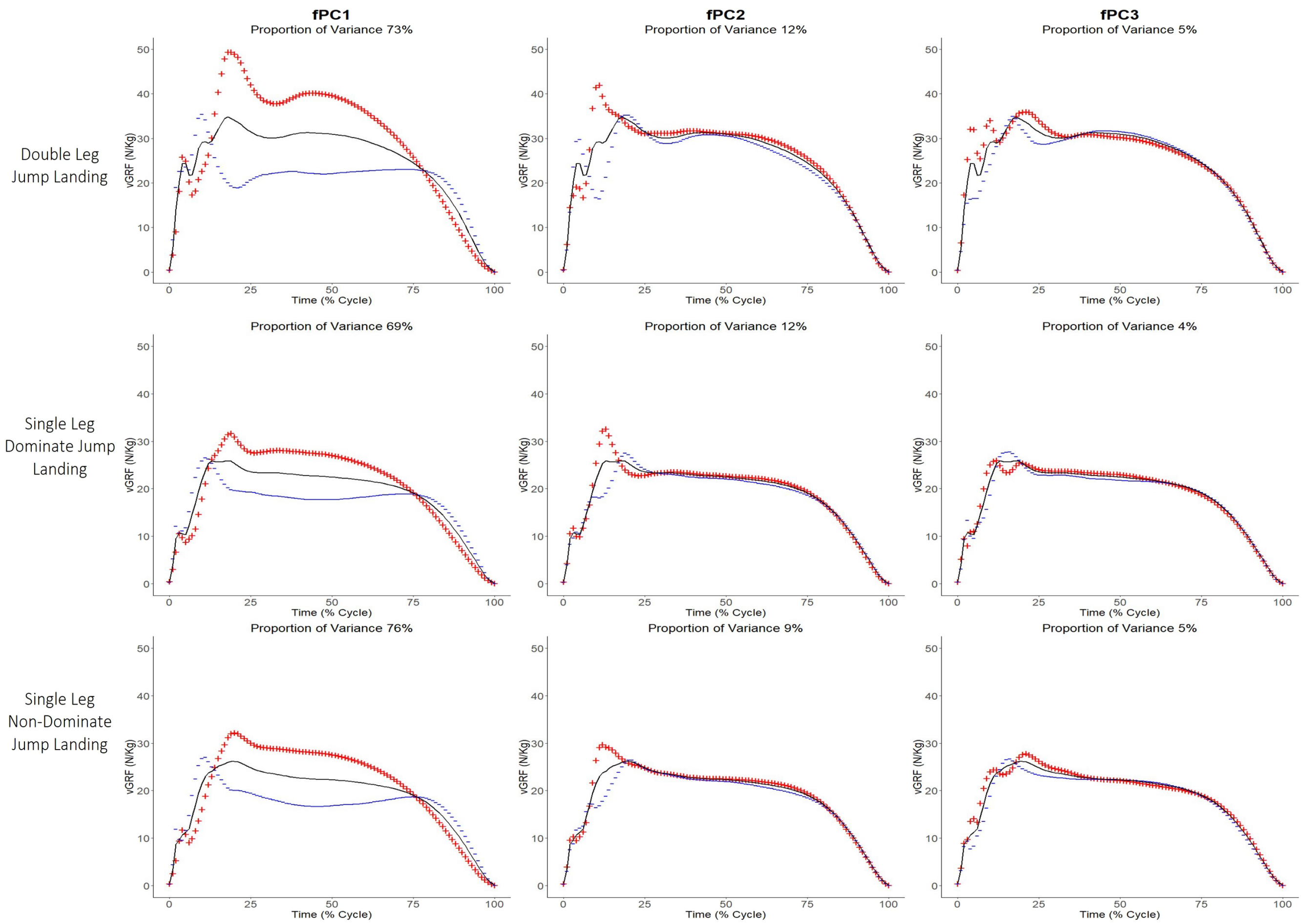


**FIGURE 1** Summary of low-risk and high-risk landers force time curves analyzed using fPCA. Key fPC's (1–3) and the proportion of variance each account for was analyzed and plotted for each jump landing task. The "+" red curve represents high-risk landers average force time curve for the principal component. The "-" blue curve illustrates the low-risk lander groups force time characteristics. The black line depicts the cohorts average force time curve. fPC = functional principal component; N/kg = Newtons per kilogram; vGRF, vertical ground reaction force.

jumps landings accounted for 90% of the total variation (Figure 1). Whilst fPC's one to three accounts for 85% of the total variance for SLD jump landings.

Significance (*p*-value) and relationships (R) between fPC scores and scoring system scores are shown in Table 4.

The strongest positive relationships between fPC scores and landing error scores across all three jump landings tasks are demonstrated in Figure 2.

Figure 2 shows significant differences exist between low-risk and high-risk DL landers fPC1 scores. A strong positive relationship was also present for mean LESS and fPC1 scores during the DL landing task, suggesting higher LESS scores are associated with higher fPC1 scores. Significant differences between landing quality groups fPC1 scores is also apparent in the SLND landing task, with a moderate positive relationship being observed in the SLND group. No significant differences or relationship was observed between low-risk and high-risk landing groups mean SL-LESS and fPC1 scores for the SLD jump landing task.

## 4 | DISCUSSION

The primary purpose of this study was to identify differences in the force-time characteristics of athletes displaying high- and low-risk landing profiles. Supporting our hypothesis, subjective ratings of landing technique between low-risk and high-risk landers are also evident in the shape of their force-time curves. Notably, complementing qualitative landing scores with curve analysis showed a significant relationship exists between the number of technical errors present during landing (LESS scores) and force-time characteristics (fPC1) thought to place landers at an increased risk of injury. This highlights that independently evaluating movement quality utilizing traditional performance measures or qualitative screening tools alone may have resulted in this information being discarded. Therefore, supporting the perspective of developing an individual risk profile to help provide a deeper understanding of the complex interactions influencing injury risk.[32]

Previous in vitro (cadavers) research has quantified the consequences (ACL and medial collateral ligament (MCL) strain) of varying risk classifications during simulated landings.[33] Despite these findings the mechanical stresses placed on the body (in vivo) thought to determine degree of injury risk are unknown.[34] As expected, findings from fPCA identified dangerous and safer landers are exposed to unique force profiles throughout the entire movement and during subtle sub-phases of landing. Different loading patterns observed over the entire movement is described in fPC1 (Figure 1.). Key features in this component explains most (69%–76%) of the variation between landing ability groups. Specifically, fPC1 identified high-risk landing profiles ("+" curve) are associated with larger peak $vGRF_{N/kg}$'s, which subsequently translates to greater forces experienced throughout landing (23%–50% landing cycle). Complementing the magnitude variability described in fPC1 with whole movement contact times

**TABLE 4** Relationship landing and fPC score summary

| Jump landing task | | fPC1 | fPC2 | fPC3 |
|---|---|---|---|---|
| DL | *R* | 0.805 | 0.272 | 0.074 |
| | *p*-Value | <0.001* | 0.139 | 0.691 |
| SLD | *R* | 0.251 | −0.083 | −0.289 |
| | *p*-Value | 0.173 | 0.655 | 0.114 |
| SLND | *R* | 0.568 | 0.061 | −0.202 |
| | *p*-Value | <0.001* | 0.745 | 0.276 |

Abbreviations: DL, double-leg; fPC, functional principal component; R, relationship; SLD, single-leg dominant; SLND, single-leg non-dominant.
*Indicates a *p*-value < 0.05 between low and high-risk landers.

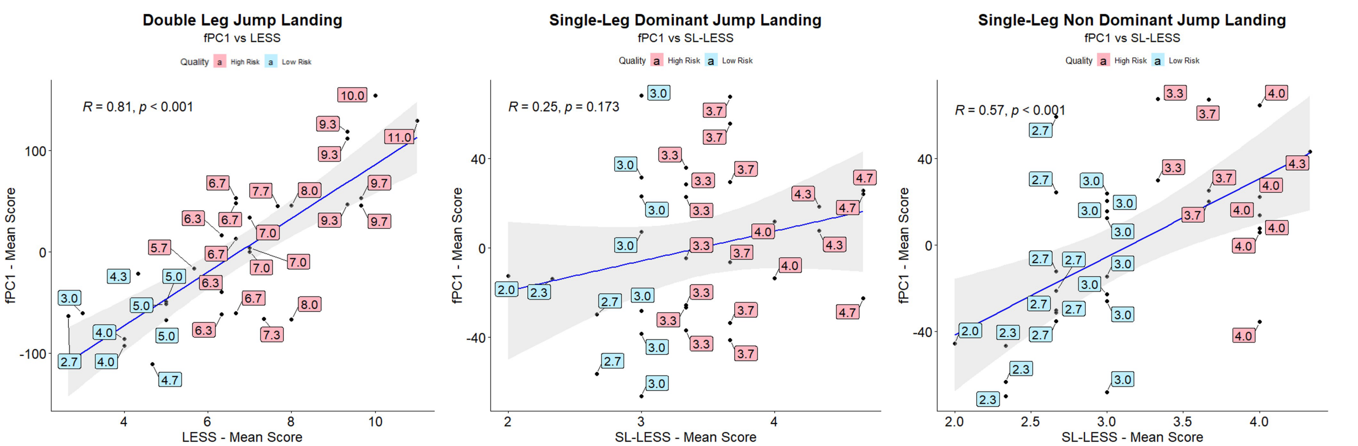


**FIGURE 2** Linear relationship between mean lander fPC1 scores and landing quality scores for each jump landing task. fPC1 scores determined form continuous force time data. DL jump landings scores assessed from the LESS. SLD and SLND jump landing scores assess using the SL-LESS. fPC, functional principal component; LESS, landing error scoring system; R, relationship; *p*, *p*-Value; SL-LESS, single-leg landing error scoring system.

(Table 2.) suggests high-risk landers are exposed to larger forces over a shorter period of time. Similar magnitude features have been observed previously using a simplified version of the LESS to determine landing ability.[35] Although not the primary purpose of Frank and colleagues research, visual comparisons suggest in a pre-fatigued state poor and excellent landing profiles displayed similar force-time characteristics to the matched high-risk and low-risk profiles in this study.[35] Consistent "high-risk" landing features observed seem to indicate a stiffer multi-joint landing profile previously identified in unilateral[36] and bilateral[37] landing studies. This extended joint position is often suggested to be a biomechanical explanation for ACL injuries,[3,19] stemming from the excessive anterior shear forces straining the passive structures within the knee.[36,37] Although a significant contributor to ACL loading,[3] anterior shear forces alone do not account for the combined strain placed on passive structures during dynamic movements.[3,19] Although outside the scope of the current study, future work should look to investigate the multi-directional loading (i.e., anterior–posterior, medial-lateral) associated with safe and high-risk landing profiles. This approach may help shed light on the combined and specific directional loading placed on the body during various landing strategies.

Additional insights from high order fPC's (fPC2 and fPC3) highlight subtle loading pattern differences between landing quality groups during the impact phase of landing (0%–30% landing cycle). Coupling results from higher order fPC's (Figure 1.) and traditional performance measures (Table 2.) indicates athletes with high-risk landing profiles are required to rapidly dissipate larger peak forces (Peak vGRF N/kg) over shorter (DL) or a similar (SLD and SLND) amount of time (time to peak vGRF). This rapid force absorption phase of landing is of particular interest as ACL ruptures (within approximately 67 milliseconds)[25,38,39] have been reported to occur during this short period of time. Video analysis has identified landing with the rear portion of the foot or flat-footed, as a common non-contact ACL injury scenario.[40] Supporting the dangers of rearfoot landings, Self and Paine[41] found a flat-footed landing strategy exposed landers to greater $vGRF_N$'s compared to other landing strategies. In contrast, a plantarflexed ankle position at initial contact reduced $vGRF_N$ exposure by maximizing the energy absorption capabilities of ankle plantar flexors. As shown in the present study, "low-risk" landers (fewer technical errors) likely utilized this advantageous foot position at initial contact to effectively dissipate rapid $vGRF_{N/kg}$'s, compared with high-risk landers. However, this single joint position does not consider the multi-joint alignment further up the kinetic chain, suggested to also influence force absorption.[34] Future studies are needed to investigate the force-time characteristics associated with specific joint positions. Constructing a landing curve library by isolating and documenting joint-specific curve characteristics equips practitioners with a resource to visually interpret safe and high-risk signal features.

Further analysis revealed a significant strong positive relationship ($R = 0.81$, $p < 0.01$) exists between LESS scores and fPC1 scores, indicating that as more technical errors are observed during DL landings fPC1 scores likely increase. This observation highlights the LESS' ability to effectively identify safe and high-risk force-time curve characteristics associated with increased risk of ACL injury. Findings from this study complement Padua's et al. 2009[12] initial research, suggesting differences observed between landing quality groups are not restricted to multi-joint angles, moments, and discrete magnitudes used to validate the screening tool. Although not the gold standard movement screening approach,[9] this study's results support the LESS's potential as a feasible field-based screening tool to effectively differentiate between safer and high-risk landing profiles.[29] In comparison, weak (SLD) to moderate (SLND) relationships were observed between SL-LESS scores and whole movement landing patterns observed in fPC1. As the SL-LESS is a relatively new and under-researched screening method that is yet to be validated,[13] these findings are somewhat expected. However, considering SL screenings offer a more sports-specific risk assessment reflecting the demanding unilateral events where ACL injuries typically occur.[9] Future work validating the SL-LESS' scoring criteria and threshold score will provide practitioners with an easily implementable alternative to traditional DL landing quality assessments.

Landing performance is traditionally quantified using single magnitudes (peak vGRF) and time points (time to peak vGRF).[4,5,18] However, results from this study and previous work[20,21] highlight limitations with this approach. Restricting this study's results to traditional performance measures (Table 3) would have limited findings to significantly longer contact times across all landing tasks. This is in line with Stephens et al.[21] previous work, showing sparse findings from single time and magnitude performance measures compared to the loading variability described from fPCA. Specially authors found peak $vGRF_{N/kg}$ was a poor measure at identifying modifications in an athlete's landing profile post injury.[21] However, Stephens et al.[21] case study was limited to a single athlete, pre- and post-injury and did not qualitatively assess landing quality. Quality curves observed in the present study provide novel insights into the movement strategies of healthy athletes, in addition to supporting a better understanding of curve features associated with ACL injury risk. Expanding on this study and previous work, future large cohort research should look to utilize curve analysis to better understand athletic movement pre- and post-injury. Phase-specific movement analysis may highlight consistent loading strategies linked with subsequent injury occurrence and help pinpoint dangerous compensatory patterns utilized post-injury. Such information will further support practitioners' ability to detect movement deficits and intervene before injuries (re)occur.

The battery of tests in the present study provides practitioners with a movement screening approach suitable for most performance support environments to evaluate and monitor athletic movement quality. Assessing both qualitative and quantitative measures during sports-specific tasks (DL, SLD, and SLND) seems to be a well-accepted screening approach to determine risk and risk tolerance.[42] Developing a baseline movement profile can serve as a benchmark for comparison, ensuring desired training adaptations have been achieved in both healthy[43] and rehabilitating contexts.[44,45] Examples of this monitoring approach are shown in previous ACL return to play case studies.[44,45] Both studies outline how baseline (healthy) data collection combined with early and frequent testing post-injury helps quantify trainable movement deficits and monitor training program effectiveness.[44,45] Despite both studies reporting a full recovery of interlimb capacity (i.e., asymmetry), functional deficits may remain.[44] Although not assessed in the present study, utilizing force-time curve analysis to compare interlimb loading strategies may have identified persistent functional deficits not identified using traditional asymmetry methods. Nevertheless, this reinforces the need for routine testing to support multi-disciplinary performance team decision making throughout the return to sport/performance transition and in "presumably healthy" contexts.[44,45]

Safe and high-risk force-time curve features demonstrated in this study provide a point of comparison for multi-disciplinary performance teams when visually analyzing loading strategies associated with ACL injury risk. It is important to note that the landing ability curves presented in this study are specific to the LESS and SL-LESS landing protocols, and future research is needed to examine the force-time characteristics of high-risk movement profiles in other sports-specific movement tasks (cutting). Ideally, using 3D motion analysis in the present study would have provided a "gold standard" evaluation of landing ability. However, accessibility to this expensive technology was limited, further supporting the need for validated field-based qualitative screening tools. Additionally in the absence of force plates, this study's results also support the use of the LESS as a valid and reliable assessment of landing quality. Alternatively, practitioners wishing to identify movement patterns potentially masked during DL assessments may also want to use a single-leg landing assessment like the SL-LESS.[9] However, as the SL-LESS is still in its infancy, further exploration is needed to validate the scoring criteria against mechanisms of ACL injury. It is acknowledged that the controlled nature of the screening protocols used in this study may not reflect the complex situations where injuries typically occur, however this assessment method enables accurate comparisons between groups. Furthermore, calculating overall landing ability using the average score from three jumps may include both high-risk and low-risk landings. Despite this, calculating the average score is common practice throughout previous research and is recommended over single-trial methods.[26] Practitioners wishing to develop targeted intervention strategies from landing quality scores should look to identify specific landing errors (items) from cumulative landing scores and monitor the effectiveness of intervention programs using a complementary (qualitative and quantitative) screening approach as observed in this study. The current study also demonstrates the potential continuous ground reaction force data to be used in the testing and development of future clinical prediction models and associated clinician diagnostic tools. It should be acknowledged, however, that more appropriate and robust methods for making predictions on functional data should be explored in these contexts (rather than exploratory processes such as PCA). These could draw on classical FDA methods like functional regression (for smaller numbers of inputs) and also extend to functional data boosting[46] or regularization methods for functional data,[47] which are more useful when the number of functional predictors grow. In any case, this is an area for future collaboration between biomechanics, sports medicine, and the statistics communities.

In conclusion, this study highlights the benefits of assessing the entire movement cycle using continuous analysis techniques (fPCA). fPCA identified differences in the landing characteristics of low-risk and high-risk landers across the entire movement and during specific sub-phases of landing that may have been discarded using traditional performance measures and qualitative screening assessments. Ideally, practitioners should look to complement screening results from force plate analysis with qualitative movement assessments to gain a better understanding of the multifactorial nature of athletic injuries. In settings where force plates are not feasible, the LESS provides practitioners with a valid and reliable assessment of DL landing quality. Alternatively, the SL-LESS offers a single-leg risk assessment, however future research is needed to validate the SL-LESS's scoring criteria and cut point.

### 4.1 | Perspective

Complexities surrounding current screening practices used to identify modifiable risk factors associated with lower-limb athletic injury have been highlighted in previous research.[17] Difficulties associated with implementing 'best practice' movement analysis methods have made determining injury risk a challenging task for practitioners and coaches.[9] Adding further complexity, feasible screening tools available to practitioners such as qualitative screening tools and quantitative traditional performance measures' ability to predict injury is questioned.[5,15] Testing properties using single time points to measure overall performance may be an inadequate approach when risk-profiling dynamic movements.[21] The present study showed continuous analysis provides an innovative alternative to traditional movement analysis approaches, identifying phase-specific mechanical loading differences between safe and high-risk landers. Incorporating powerful analytical methods such as fPCA and machine learning models into force-plate software may offer a unique opportunity to streamline the injury risk process. This synergy enables the capacity to classify high-risk loading strategies (i.e., "high-risk" curves) existing during sports-specific movement patterns. Ideally, this automated process provides immediate feedback to practitioners post-movement by analyzing dangerous force-curve characteristics within computer software, removing biases associated with visually inspecting features. Such innovation is expected to reduce preventable (re)injury occurrence and subsequently mitigate associated negative performance and health-related costs.

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## CONFLICT OF INTEREST

The authors have no known conflicts of interests to declare.

## DATA AVAILABILITY STATEMENT

The data are not granted ethical approval for open access release under a CC-BY 4.0 license, given that data pertains to athletes being monitored as a part of their involvement with an Australian state government organization. Specific requests can be lodged with the first author of the paper regarding methods and if necessary, retrospective ethical release of the data can be sought depending on the request being lodged after publication.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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## APPENDIX 1

## CURVES & KINEMATICS: RELATIONSHIP BETWEEN THE FORCE-TIME CURVE AND LANDING ABILITY

### fPCA: A practical description

### PCA

Principal components analysis (PCA) is an exploratory statistical method used to explore structures of variability that are present in multivariate datasets. PCA is used to identify "new variables" present in multivariate data, often referred to as principal components (PCs), with these new variables representing linear combinations of the original data. The original data is organized into these new linear combinations relative to the covariance structures present in the original multivariate data.

This takes place via a matrix transformation, where the original data matrix (X) is used to create two new data matrices. The model describing this is $Z = UX$, where the columns of the matrix $U$ are called principal component loading vectors, and are the eigenvectors of the covariance matrix of the original data matrix (X). The principal component score (PC score) vectors (which represent the columns of Z), are composed of the coefficients which measure the contribution of the principal components to each individual multivariate observation. The principal component model can also be inverted so that, $X = UZ$, such that the original data can be reconstructed from the principal components and the scores for each of the components, for each observation.

What this means is that the two matrices represent a new way of describing variability in the original. The principal component loading vectors (i.e., U matrix), provide a "weighting" for each of the original variables, according to how much each of the original variables are contributing to this new variable (or PC). The larger the weighting on a particular variable (i.e., larger the value), the more that variable is contributing within a PC. The scores for each PC (i.e., Z matrix) are a value given to each observation, relative to each PC, representing how much each PC contributes to representing the original observations. So hypothetically, for 100 observations, if there are 5 new variables constructed (i.e., 5 PCs) from an original set of 30 variables, each variable will have a weighting within each of the 5 PCs, and each of the 100 observations will have a score for each PC (i.e., a score for PC1, a score for PC2).

### *f*PCA

Functional PCA (*f*PCA) is mathematically an extension of PCA for use with functional data, and several preliminary steps are required prior to application, with a full outline of these available in (Warmenhoven et al., 2021). The main and important difference between PCA applied to multivariate data, and *f*PCA applied to time-continuous data, is that time-points are used rather than variables. Additionally, the eigenvectors of the covariance matrix (i.e., U matrix), are also eigenfunctions relative to time (as the original data are functions or curves), with the weighting applied along the time continuum rather that to individual variables. The Z matrix is again representative of *f*PC scores.

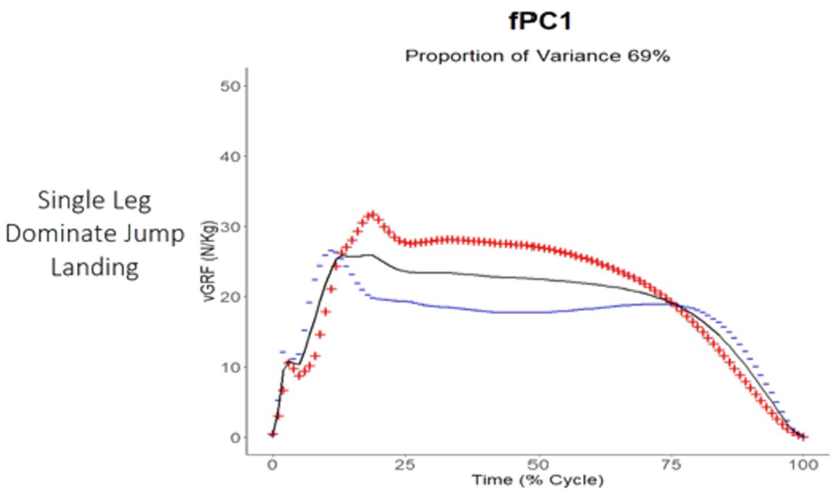
### Graphically interpreting fPCA

Ramsay and Silverman (2005) have recommended the use of graphs that present the ensemble mean function, together with each *f*PC added and subtracted from the mean. The addition of an *f*PC is demonstrated using the "+" symbols, and a subtraction from the mean with the "−" symbols.

Scores mirror the visual presentation of these PCs, with positive scores resembling a pattern in the original curve that moves away from the mean, in the direction of the "+" line (or across the region where the "+" line is most different). The same is true for negative scores, and the "−" line. The larger a positive or negative score, the further it moves away from the mean in the direction described by the *f*PCs.

### Take home for clinicians or practitioners using fPCs to understand curves

*f*PCA takes a group of curves, represented as functions, and then reduces them into new outputs that are easier to interpret statistically. The outputs come in two steps. The first steps are the *f*PCs, or loading vectors, which describe how the waveforms are varying across different parts of the movement (with some parts having much high loadings than others within a PC). This makes the *f*PC outputs descriptive but linked back to the original characteristics of the curves. The second steps are the scores, and these represent how much each *f*PC is describing characteristics of the original curves. If a score for a given *f*PC is strongly positive or negative, that *f*PC is strongly contributing to the structure of that observation. As such, statistical tests (i.e., regression models, classification methods) can be applied to the scores to see whether an *f*PC (or a combination of them) describe differences between groups that may be a part of a particular research question.




*A summary of low and high-risk landers force time curves analysed using fPCA. Key fPC1 and the proportion of variance each account for was analysed and plotted for the single leg dominant jump landing group. The "+" red curve represents high-risk landers average force time curve for the principal component. The "-" blue curve illustrates the low-risk lander groups force time characteristics. The black line depicts the cohorts average force time curve. fPC = Functional Principal Component, vGRF = Vertical Ground Reaction Force, N/Kg = Newtons per Kilogram.*