**Increased leap performance and no change to knee-drop landing kinetics, following a verbal cueing intervention.**

**Abstract**

**Introduction**: Knee-drop landings following a dance leap are often used in contemporary dance choreography, but there is limited research into the biomechanical demands of these types of landing. This study aimed to investigate the effects of a verbal cueing intervention on the performance and kinetics of a common knee-drop landing in contemporary trained dance students.

**Method**: Pre-vocational dance students participated in this study (n = 8). A quasi-experimental research design was followed to collect kinematic and kinetic data using 3D motion capture and force plates following the take-off and during a knee-drop landing of a contemporary dance style leap pre and post a verbal cueing intervention. Performance variables analysed were jump height and flight time, while kinetic variables included vertical ground reaction forces (vGRFs) and loading rates. **Results**: A statistically significant increase in jump height and flight time was found post intervention; There was no significant difference between pre and post intervention for peak vGRFs at foot or knee impact or loading rate of the whole landing phase.

**Conclusion**: The verbal cueing intervention was successful in increasing flight time and jump height, indicating optimised performance. The lack of significant difference in peak vGRFs and loading rate in the landing phase implies that the intervention did not have a detrimental effect on musculoskeletal loading. These findings demonstrate the positive influence of a verbal cue which focusses on increasing flight time and opposing the landing for enhancing the execution of a dance leap without negatively affecting the forces being experienced in the knee-drop landing that followed. However, it should be noted that the small sample size and lack of a control group in this study may limit the reliability of findings and mean that the generalizability of these findings should interpreted with caution.

**Word Count: 291**

**Keywords**: biomechanics, contemporary dance, knee-drop landings, cueing, ground reaction force

**Key points**

 **1.** A verbal cueing intervention which focused on suspending in the air and opposing the landing was successful in increasing flight time and jump height of a dance leap.

 **2.** Increased flight time and jump height did not result in increased peak vGRFs or loading rate during the knee-drop landing.

 **3.** Performance optimisation of a dance leap can be achieved via a verbal cueing intervention without detrimental effect on musculoskeletal loading.

**Introduction**

Contemporary dance requires expressivity and artistic virtuosity as well as athleticism. A dancer is required to meet ever changing choreographic demands even if movement may not be biomechanically sound to perform. Ideally, dancers, teachers and choreographers should understand the consequences associated with the stressors of specific movement tasks, to promote enhanced biomechanical strategies and minimise potentially harmful impacts, while maintaining optimal performance outcomes. It has been found that ground reaction force (GRF) is an indicator of the stress experienced by the body as contact is made with the ground1. If ground reaction forces are too high for the musculoskeletal system to disperse, there is an increased injury risk2,3. Loading rate (the speed at which these forces are experienced by the system), can also be a factor in the level of injury risk due to poor shock absorption and force distribution if the loading rate is high4.

Choreographic demands spanning a breadth of genres, including contemporary dance, often dictate the use of knee-drop landings following a leap. In this action, dancers land on the top of their foot, folding the leg underneath as the weight is taken through the front of the lower leg on to the knee before continuing into a seated roll to the side. These landings occur in a range of settings from young recreational dancers, to students in vocational training, to professional dancers. The technique required to underpin such complex movement is not always taught correctly and sometimes self-taught, potentially resulting in detrimental musculoskeletal loading when striving to enhance performance outcomes such as flight time and jump height, especially in those who may not be sufficiently physically conditioned to cope with the stressors caused by the impact. The frequency with which these types of landings have been observed in practice and the lack of existing research exploring landing forces prompted this investigation.

Previous research into landing from dance leaps has focused on landings through the foot,5-8 and primarily considered the relationship between landing forces and injury risk,9-13 with GRF being identified as a key factor affecting professional dance injuries14. One study14 compared the landing from different jumps across three dance styles: classical dance, modern dance, and Polish folk dance, reporting that jete-like leaps produced significantly higher GRFs than other types of jumps measured. Gorwa and colleagues also reported that classical dancers produced significantly higher GRF’s than the other dance styles, which was explained by the short duration required of the timing of the landings in classical dance leaps, in comparison to the longer landing phases seen in the modern dance leaps. In sum, existing research in foot-based dance landings identifies that different dance actions, different landing techniques, and rate of loading during the landing phase influences vGRF and subsequent potential injury risk.

A study by Van Ramshorst and Choi15 investigated peak knee and hip contact vGRFs, percentage of Maximum Voluntary Isometric Contraction (%MVIC) of rectus femoris and gluteus medius muscles, and time to peak vGRF during the landing phase of collegiate-level contemporary dancers during two techniques of a choreographed fall on to the lower leg. Technique one utilised an anterior fall, landing through ankle plantarflexion, knee, and hip flexion to disperse forces through the anterior shank, whereas technique two was a laterally focused fall through ankle inversion and a dispersion of forces through the lateral aspect of the shank. It was found that technique two produced lower peak vGRF at knee contact, along with increased muscle activity of the rectus femoris and gluteus medius, and increased time to knee contact, which they suggest contributed to the reduced forces.

Parkour athletes are also required to execute non-traditional landings. In this movement form research has found that a landing technique which extends the duration of the landing phase produces lower peak GRFs. Puddle and Maulder16 compared the vGRF and loading rate of a traditional drop landing which lands on the forefoot and lowers to the rear-foot, with two other types of Parkour landings; a Parkour precision landing, which involves the forefoot landing on to a precise object such as a handrail, and a Parkour roll, which lands on the forefoot, continuing into a roll over the shoulder. It was found that the Parkour precision and roll landings demonstrated significantly less maximal vGRF and loading rates than the traditional landing, but no significant difference between the precision or roll landings. Research by Maldonado et al.,17 into Parkour precision landings found that in comparison to untrained participants, Parkour athletes extended the duration of the landing phase with increased knee range of motion, producing lower GRFs in all directions. Dai et al.,18 continued to investigate the kinematics of landings in Parkour, comparing landings from three heights utilising four techniques; squat, forward with hands on the floor, roll and stiff landing. Findings from these studies reinforce the loading rate principle4; stiff landings may increase injury risk due to the sudden decrease of vertical velocity over a short duration, whilst the roll landing decreased peak loading on the lower extremities due to the decrease of vertical and horizontal loading over a longer duration.

In dance and other movement contexts, verbal cues are frequently used to provide instruction and feedback, with the intention of adapting technical execution and optimising performance19. Insights from motor learning and skill acquisition in sport, and more recently in dance, indicate that verbal cues which focus on directing attention can influence performance outcome. Focus of attention is defined as the ability to identify, direct, and sustain one’s attention on information relevant to task accomplishment20. To date, research across a range of sports identifies an external focus of attention (e.g., focusing on the intended effect of the movement) is more effective than internal focus of attention (e.g. an instruction which focuses on specific body movements) at achieving desired performance outcomes20,21 Generally, research into the effects of dance instruction is scant,22 has mostly centred on imagery23 rather than instructional verbal cueing or direction of attentional focus, and no studies were identified that examined the effects of instructional cueing on vGRF in dance. One study24 reported that biofeedback (seeing and receiving an explanation of the vGRF) following an initial performance of a modern dance jump resulted in an increased duration in contact time, and increased duration from point of contact to peak vGRF, with a subsequent reduction in peak vGRF and loading rate, suggesting that a biofeedback intervention may reduce jumping impacts in subsequent performances. However, not every dancer or dance instructor will have access to the required equipment to provide such biofeedback, and the long-term effects have not been researched. In recreational athletes, research into the effectiveness of verbal instruction when landing from a 30cm drop jump found that kinematics-focused instructions resulted in a 13% decrease in peak GRF through the lower limb25 and a 21% decrease following technical instruction26. Combined, it can be assumed that an instructional intervention which centres on the execution of a given movement is likely to influence future performances of a baseline movement, and these effects may be evident in both performance and kinetic variables. Therefore, the aim of this study was to measure the effects of a verbal cue on the performance and kinetics of a knee-drop landing following a dance leap in pre-vocational dance students.

**Methods**

***Participants***

An opportunistic sample of ten female participants (Mean 17 ± 0.9 years, 60.7 ± 9.2 kg, 157.8 ± 7.2 cm) volunteered for the study. Mean dance experience of the participants was 9.8 ± 6.0 years, with a minimum of 3 years and a maximum of 16 years. Participants were required to have expertise in performing the movement being observed and be able to perform it repeatedly with success. The participants were currently enrolled in pre-vocational training at a leading Performing and Creative Arts school in the UK, specialising in Dance forms such as Contemporary, Jazz, Ballet, Tap and Street Styles. No participants reported any musculoskeletal injury or neurological condition which prevented them taking part. Participants were barefoot and wore black leggings or tights and a tight fitted dark top or leotard to provide clear contrast for the retro-reflective markers and to reduce the effect of friction burn from landing on the carpeted surface.

***Ethics Approval***

Ethical approval was granted by the author’s University Ethics Board, and informed consent was provided by each participant, prior to data collection.

***Study Design***

The study followed a quasi-experimental research design measuring kinematic and kinetic variables following the take-off and during a knee-drop landing of a contemporary dance style leap, pre and post a verbal cueing intervention.

***Procedures***

The participants completed a self-directed warm up lasting 5 minutes. This was observed by the researcher who is an experienced dance teacher to ensure parity between all participants. Retro-reflective markers (B&L Engineering, Los Angeles, UK) and lower limb custom-made marker triads (University of Chichester, West Sussex, UK)27 were then applied to the body. A lower limb marker set based on the CAST system28 was used (see Table 1), with two additional tracking markers placed on the inside of each foot on the navicular tuberosity, and on the sacrum. Six upper body markers were placed on the right and left acromion, sternum jugular notch, C7 and T10 vertebrae and the sternum xiphisternal joint. After the static calibration trial was recorded, markers were removed from the lateral malleolus and lateral femoral epicondyle of the landing leg, and the second and fifth metatarsal heads of each foot, to allow the participants to complete the required movement successfully without discomfort.

*[Insert Table 1 here]*

Data was collected using Vicon infrared cameras (MX T-Series (T40-S) Camera, Vicon Motion Systems Ltd, Oxford, UK) recording at 250Hz. GRF was measured using a Kistler Piezoelectric force plate recording at 1000Hz (Type 9287, Kistler Instruments, Hampshire, UK).

Participants were instructed to select their preferred leg to perform the landing on, based on which side they would feel confident in their ability to accurately perform the required movement successfully and safely. The same instructions were given to each participant. The movement began from a parallel standing position, with the feet aligned underneath the hips, and the weight equally distributed between both legs. The participant then stepped one foot across the other, before using their non-preferred leg to push off into a sideways leap, with both hips externally rotated, flexed, and abducted, knee of the leading leg flexed, knee of trailing leg fully extended, ankle and foot plantarflexed, and arms abducted to shoulder height. The leading leg remained folded in the air with the trailing leg brushing to extend to second position. Initial ground contact in the landing was made by the dorsal surface of a plantarflexed ankle and foot, followed by the shin and knee as the dancer folded the leg underneath themselves, then transferred the weight to the side of the hip and continued into a seated roll across the back of the pelvis. The analysis of vGRFs was stopped after the point of knee impact so that hand contact made with the force plate during the roll would not impact GRF measures. Figures 1a to 1e visually represent the phases of the movement. To finish the movement the dancers immediately stood up on the same leg used to land the leap and ran in a semi-circle around the front of the force plate back to their starting position. This continuous sequence of movement was used to replicate a typical demand of choreography, where the dancer would usually be expected to continue from one movement straight into another29.

*[Insert Figures 1a to1e]*

The movement was performed to a metronome of 106bpm as this has been referenced as a typical tempo used in a dance class30. Participants were instructed to begin standing to the side of the force plate, at a distance that enabled them to complete the movement and land both the foot and the knee on the centre of the force plate. The starting point was marked with tape to ensure that every trial for each individual was consistent and comparable31. A trial was deemed successful if the dancer landed on the force plate with both the foot and the knee after performing the movement with the required quality and technical control. Prior to data collection, the dancer was given 5 minutes to practice the movement and undertake familiarisation trials.

Five pre-intervention trials, with 30 seconds rest in between were recorded. Following this, a verbal instruction cue was given; “on your next repetition think about suspending in the air for longer and opposing the landing.” The verbal cue aimed to enhance performance outcomes of flight time and jump height, while simultaneously aiming to slow down the landing, tapping into the loading rate principle of distribution of force across time4. The instruction of “opposing the landing” aimed to improve the dancers’ landing technique by reducing the landing forces on impact, as GRF has been identified as a key factor affecting professional dance injuries14.The wording purposefully created an external directional focus, as this has been identified as beneficial in achieving desired performance20.Following the cueing intervention, the participant performed five post-intervention trials, whilst attempting to apply the cue.

***Data Analysis***

The data was processed and labelled using Vicon Nexus software version 2.14.0 (Vicon Motion Systems Ltd, Oxford, UK). Due to marker occlusion, the clearest three pre and post trials for each participant were selected based on the visibility of the marker trajectory throughout the whole movement. Two participants were excluded from the analysis due to errors in data collection. Therefore, trials from eight participants were used in data analysis.

Visual 3D software (C-Motion, Inc., Germantown, Maryland, USA) was used to model the motion and force data. An eight-segment model included the pelvis, trunk, left and right thigh, shank and foot segments. A low pass Butterworth digital filter with a cut off frequency of 30Hz was applied to original marker trajectories based on published literature32 and upon visual inspection of the data. On visual inspection, the start of flight duration was identified as the take-off foot leaving the ground. Initial contact of the foot on the force plate was identified using a threshold of 10N33. The critical events of peak vGRF at foot impact and knee impact in the landing phase were extracted from the data and are identified in figure 2 on a representative vGRF signal. The knee impact phase ended when, upon visual inspection, the dancer made hand contact with the ground. Variables of flight time (s), jump height (m), peak vGRF (N) at foot impact and peak vGRF (N) at knee impact were extracted. Loading rate was calculated from initial foot contact on the force plate to the peak knee vGRF.

*[Insert Figure 2]*

***Statistical Analysis***

To allow a comparison across participants, force data for all participants (n=8) included in the data analysis was normalised to bodyweight by dividing the magnitude of the peak vGRF by the subject’s body weight (N) to produce a value expressed in units of bodyweight (BW)34. Loading rate was expressed as BW/s. R Studio (v4.2.1; R Core Team, 2022)35 was used to carry out statistical analysis. A non-parametric Wilcoxon signed rank test was used to test for difference (V) between the pre and post intervention values for each variable36, given the sample size did not meet the assumptions for a parametric paired-samples t-test. The rank biserial correlation test was used on each variable to check the effect size (rrb) and produce 95% confidence intervals (CI).

**Results**

*[Insert Table 2 here]*

Table 2 reports the pre and post values for all variables. The verbal cueing intervention was effective as indicated by the statistically significant increase in jump height and flight time from pre-to post intervention; *V* = 1.0, *p* = 0.021, *rrb* = -0.94, 95% CI [-0.99, -0.76], *V* = 1.0, *p* = 0.016, *rrb* = -0.94, 95% CI [-0.99, -0.76], respectively. The confidence interval around the effect size for both variableswas narrow, indicating good accuracy in parameter estimation.

When normalised to bodyweight, there was no significant difference between the pre and post intervention for peak vGRF at foot impact *V* = 17, *p* = 0.945, *rrb*= -0.06, 95% CI [-0.68, 0.62] or knee impact *V* = 16.5, *p =* 0.889, *rrb* = -0.08, 95% CI [-0.70, 0.60], suggesting that despite a significant increase in flight time and jump height there was no extra force exerted during landing.

There was no significant difference in the loading rate from the point of foot contact to the end of the peak knee contact between the pre intervention and post intervention conditions *V* = 24, *p* = 0.461, *rrb* = 0.33, 95% CI [-0.41, 0.81].

**Discussion**

Verbal cues are frequently used by choreographers and teachers to provide instruction and feedback, with the intention of adapting technical execution to optimise performance outcomes. The verbal cue of “on your next repetition think about suspending in the air for longer and opposing the landing” used in this study aimed to increase the elevation of the dance leap while maintaining a controlled landing. The optimisation of jump height and flight time accompanied by a ‘softer’ landing phase align with what a choreographer or teacher would likely desire as performance outcomes from this specific movement, encouraging the dancer to appear more effortless while also demonstrating athletic and artistic finesse. The wording for the cue was specifically devised to support an external focus of attention, where the focus was on spatial directions and the desired movement outcome, rather than body-based execution cues. In line with the considerable research on the beneficial performance outcomes of external attentional cues across a range of movement domains,20,21 the participants’ jump height and flight time significantly increased following implementation of the verbal cue. These findings imply that the cue was effective in enhancing the dancers’ leap performance, with reference to these specific performance variables. However, it is important to consider that a general learning effect from repeated testing may have influenced the post-intervention outcomes.

Regarding landing forces, peak vGRF (BW) at foot and knee impact showed no significant change from pre to post intervention, demonstrating that the increased jump height and flight time did not result in the dancer experiencing more force during the landing phase. Pre- and post- peak vGRF (BW) at foot impact remained consistent at 0.60 BW, and peak vGRF (BW) at knee impact was 4.22 BW pre intervention and 4.39 BW post intervention. It is difficult to directly compare these landing forces with previous literature due to the prior emphasis on foot-based landings. However, the peak knee impact forces recorded in this study are similar to GRFs of foot-only landings reported by Gorwa and colleagues14 following a modern dance grand jeté en tournant (4.67 BW) and travelling leap (5.13 BW), and by Jarvis and Kulig30 for a saut de chat (4.4 BW). In contrast, other movement forms have reported lower peak vGRF in non-foot-based landing than traditional foot-based landings, for example, a Parkour roll (landing on the forefoot, and immediately progressing to a forward shoulder roll) produced significantly lower vGRFs (2.9 BW) than a traditional landing (landing on the forefoot and lowering to the rear-foot) (5.2 BW)16. It is important to emphasise, that a dance knee-drop landing following a leap seems to produce similar forces to a foot-based dance landing, but these peak forces are experienced at knee impact rather than foot impact. Therefore, it is essential that dance teachers and choreographers effectively prepare and condition the knee and surrounding musculature to safely withstand the peak forces experienced by the eccentric loading in such landings.

The limited dance research into non-foot-based landings observed in a choreographed fall from a static position reports vGRF’s of 2.81 BW and 2.09 BW for a choreographed fall onto the lower limb anteriorly and laterally, respectively15. These lower forces can be explained by the different actions preceding the landing; a fall from standing studied by Van Ramshorst and Choi,15 and the dance leap investigated in the current study. Interestingly, however, Van Ramshorst and Choi reported significantly lower peak forces from the lateral shank focused landings with inversion of the foot, as opposed to an anterior shank focused landing with plantarflexion of the foot. The current study did not instruct the dancers on specific techniques for how to land from the leap in either pre or post intervention trials. Perhaps future studies could investigate the role of different technical cueing on peak vGRF’s.

Previous studies have noted that high loading rates have been associated with increased injury risk2, with a decrease in loading rate been found to result in less stress being placed on the system when subjected to loads experienced during an impact29. No significant difference in time to peak knee impact or loading rate in the landing phase from pre- to post-intervention was seen in the current study. It is not surprising that there was no reduction in these variables, due to the metronomic standardisation of the timing of both the leap and the subsequent landing across pre- and post- trials. However, the significant increase in jump height and flight time of the leap following the cueing intervention, risked resultant increases in the kinetic variables. It follows that if flight time and jump height increased, COM velocity at landing would increase, therefore requiring greater muscular effort to decelerate the body on impact, suggesting that following the verbal cue, dancers had to develop effective strategies to disperse the potentially increased forces during the landing. Therefore, the lack of significant difference in peak vGRF and loading rate implies the optimised performance observed in jump height and flight time was not accompanied by a detrimental effect on musculoskeletal loading. It should be noted, there was a considerable range across individual participants’ loading rates suggesting variability in the dancers’ skill level and strategies used in the execution of this specific movement task. This may be due to the pre-vocational level of the dancers.

**Limitations**

A key limitation to this study is the absence of a control group and the small sample size. The constraints of force plate size limited the movement phases investigated to landing forces only. For the purpose of the current study, only vGRFs at two key events were analysed as these were most relevant to the trajectory of the movement being investigated. Future research could benefit from including take-off data, analysis of all movement phases, peak total GRF plus lateral and rotational variables in addition to vGRFs, providing further detail to kinetic analysis.

**Practical and Clinical Applications and Implications**

A challenge when using quantifiable variables to illustrate improved performance is that aesthetic dance movements can rarely be judged by measurable outcomes alone. In the dance studio and on the stage, the success of the execution is more subjective and may depend on factors linked to artistic expression such as musicality, expressivity, and stylistic quality.37 Despite this acknowledgement, the current findings imply the cueing instruction used during this study could be used as feedback to dancers to see performance improvements in aspects of elevation and controlled landing for this specific dance movement. Additionally, teachers and choreographers should be aware of the inherent loads involved in asking dancers to perform knee-drop landings, and particularly the stress at knee impact. Therefore, dancers should be sufficiently conditioned to cope with the choreographic demands required of such landings, supporting enhanced performance potential and reduced injury risk.

**Conclusion**

In conclusion, dancers, teachers and choreographers should understand the associated stressors of specific movement tasks, to promote enhanced biomechanical strategies and minimise potentially harmful impacts, while maintaining optimal performance outcomes. This study has found that in a knee-drop landing following a dance leap the verbal cueing intervention of “on your next repetition think about suspending in the air for longer and opposing the landing” was successful in increasing performance variables of jump height and flight time. The lack of significant difference in peak vGRFs and loading rate in the landing phase following the cue implies that the intervention did not have a detrimental effect on musculoskeletal loading. These findings allow dancers, teachers, and choreographers to understand that it is possible to increase jump height and flight time, without creating additional loading stress in the knee-drop landing.

**Word Count: 3924 (not including headings, references and instructions for placements of Tables and Figures)**

**References**

1. McClay IS, Robinson JR, Andriacchi, TP, et al. A profile of ground reaction forces in professional basketball. *J Appl Biomech*. 1994;10(3):222–236. doi:10.1123/jab.10.3.222
2. Walter HL, Docherty CL, Schrader J. Ground reaction forces in ballet dancers landing in flat shoes versus pointe shoes. *J Dance Med Sci*. 2011;15(2):61-64. doi:10.1177/1089313X1101500202
3. Bates NA, Ford KR, Myer GD, Hewett, TE. Impact differences in ground reaction force and center of mass between the first and second landing phases of a drop vertical jump and their implications for injury risk assessment. *J Biomech.* 2013; 46(7):1237-1241. doi:10.1016/j.jbiomech.2013.02.024
4. Ricard MD, Veatch S. Comparison of impact forces in high and low impact aerobic dance movements. *Int J Sport Biomech*. 1990;6(1):67–77. doi: 10.1123/ijsb.6.1.67
5. Chockley C. Ground reaction force comparison between jumps landing on the full foot and jumps landing en pointe in ballet dancers. *J Dance Med Sci*. 2008; 12(1):5-8. doi:10.1177/1089313X0801200101
6. Arnwine RA, Powell DW. Sex differences in ground reaction force profiles of ballet dancers during single-and double-leg landing tasks. *J Dance Med Sci.* 2020;24(3):113-117. doi:10.12678/1089-313X.24.3.113
7. Jeon D, Bressel E, Kim NJ. Ground Reaction Forces Comparison of Sauté Jump Landing between Dancers with Different Levels of Proficiency. *J. Dance Educ*. 2024;24(1):35-40. doi:10.1080/15290824.2021.1989438
8. Chowning L, Krzyszkowski J, Nunley B, et al. Biomechanical comparison of dominant and non-dominant limbs during leap-landings in contemporary style female dancers. *J Dance Med Sci.* 2021; 25(4), 231-237. doi:10.12678/1089-313X.121521b
9. Liederbach M, Kremenic IJ, Orishimo KF, et al. Comparison of Landing Biomechanics Between Male and Female Dancers and Athletes, Part 2: Influence of Fatigue and Implications for Anterior Cruciate Ligament Injury. *Am J Sports Med*. 2014;42(5):1089-1095. doi:10.1177/0363546514524525
10. Peng HT, Chen WC, Kernozek TW, et al. Influences of patellofemoral pain and fatigue in female dancers during ballet jump-landing. *Int. J. Sports Med*. 2015;36(09):747-753. doi:10.101055/s-0035-1547220
11. Kulig K, Fietzer AL, Popovich Jr JM. Ground reaction forces and knee mechanics in the weight acceptance phase of a dance leap take-off and landing. *J Sports Sci.* 2010;29(2):125-131. doi:10.1080/02640414.2010.534807
12. Hendry D, Campbell A, Ng L, Harwood, A, Wild C. The Difference in Lower Limb Landing Kinematics Between Adolescent Dancers and Non-Dancers. *J Dance Med Sci.* 2019;23(2):72-79. doi:10.12678/1089-313X.23.2.72
13. McNitt-Gray JL, Koff SR, Hall BL. The Influence of Dance Training and Foot Position on Landing Mechanics. *Med Probl Perform Art.* 1992;7(3):87-91. [http://www.jstor.org/stable/45440556. Accessed 20th July 2023](http://www.jstor.org/stable/45440556.%20Accessed%2020th%20July%202023). https://pmc.ncbi.nlm.nih.gov/articles/PMC10928442/
14. Gorwa J, Nowakowska-Lipiec K, Michnik R. Ground reaction force as a factor responsible for the topography of injuries in professional dance. An analysis of three dance styles: classical dance, modern dance, and folk dance. *Scand J Work Environ Health*. 2024;50(2):103-112. doi:10.5271/sjweh.4137
15. Van Ramshorst C, Choi W J. Characteristics of contact force and muscle activation during choreographed falls with 2 common landing techniques in contemporary dance. *J Appl Biomech*. 2019;35(4):256–262. doi:10.1123/jab.2018-0081
16. Puddle DL, Maulder PS. Ground Reaction Forces and Loading Rates Associated with Parkour and Traditional Drop Landing Techniques. *J Sports Sci Med.* 2013;12(1):122–129. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3761764/ Accessed 14th April 2023.
17. Maldonado G, Soueres P, Watier B. Strategies of parkour practitioners for executing soft precision landings. *J Sports Sci.* 2018;36(22):2551–2557. doi:/10.1080/02640414.2018.1469226 2018
18. Dai B, Layer JS, Hinshaw TJ, Cook, RF, Dufek, JS. Kinematic analyses of parkour landings from as high as 2.7 meters. *J Hum Kinet*. 2020;*72*(1):15–28. doi:10.2478/hukin-2019-0123
19. Karin J. Recontextualizing Dance Skills: Overcoming Impediments to Motor Learning and Expressivity in Ballet Dancers. *Front Psychol.* 2016;7(431):1-7. doi:10.3389/fpsyg.2016.00431
20. Wulf G. Attentional focus and motor learning: A review of 15 years. *Int. Rev. Sport Exerc. Psychol.* 2013;6(1):77-104. doi:10.1080/1750984x.2012.723728
21. Wulf G, Lewthwaite R. Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. *Psychon Bull Rev*. 2016;23(5):1382-1414. doi:10.3758/s13423-015-0999-9
22. Soerel BF, Plaatsman LA, Kegelaers J, Stubbe JH, van Rijn RM, Oudejans RRD. An analysis of teachers' instructions and feedback at a contemporary dance university. *Front Psychol*. 2023;14:1133737. Published 2023 Apr 27. doi:10.3389/fpsyg.2023.1133737
23. Muir, IL, Munroe-Chandler, KJ. A scoping review of empirical research on dance imagery. *Int. Rev. Sport Exerc. Psychol.* Published 2023 Oct 22 doi:10.1080/1750984X.2023.2266814
24. Gorwa J, Michnik R, Nowakowska-Lipiec K. How to teach safe landing after the jump? The use of biofeedback to minimize the shock forces generated in elements of modern dance. *Acta Bioeng Biomech*. 2021;23(3):47-59.
25. McNair PJ, Prapavessis H, Callender K. Decreasing landing forces: Effect of instruction. *Br. J. Sports Med.* 2000;34(4):293-296. doi:10.1136/bjsm.34.4.293
26. McNair PJ, Prapavessis H. Effects of Instruction in Jumping Technique and Experience Jumping on Ground Reaction Forces. *J. Orthop Sports Phys Ther.*,1999;29(6):352-356. doi:10.2519/jospt.1999.29.6.352
27. Augustus S, Hudson PE, Harvey N, Smith N. Whole-body energy transfer strategies during football instep kicking: implications for training practices. *Sports Biomech*. Published online July 27, 2021. doi:10.1080/14763141.2021.1951827
28. Cappozzo A, Catani F, Leardini A, Benedetti M, Della Croce U. Position and orientation in space of bones during movement: Experimental artefacts. *Clin Biomech*. 1996;11(2):90–100. doi:10.1016/0268-0033(95)00046-1
29. Chowning L, Krzyszkowski J, Nunley B, et al. Biomechanical comparison of dominant and non-dominant limbs during leap-landings in contemporary style female dancers. *J Dance Med Sci.* 2021:25(4):231–237. doi:10.12678/1089-313x.121521b
30. Jarvis DN, Kulig K. Lower extremity biomechanical demands during Saut de chat leaps. *Med Probl Perform Art.* 2016;31(4):211–217. doi:10.21091/mppa.2016.4039
31. Myer GD, Bates NA, DiCesare CA et al. Reliability of 3-dimensional measures of single-leg drop landing across 3 institutions: Implications for Multicenter Research for secondary ACL-injury prevention. *J Sport Rehabil*. 2015; *24*(2), 198–209. https://doi.org/10.1123/jsr.2014-0237
32. Kristianslund E, Krosshaug T, van den Bogert AJ. Effect of low pass filtering on joint moments from Inverse Dynamics: Implications for Injury Prevention. *J Biomech*. 2012;45(4):666–671. doi:10.1016/j.jbiomech.2011.12.011
33. Tirosh O, Sparrow WA. Identifying Heel Contact and Toe-Off Using Forceplate Thresholds with a Range of Digital-Filter Cutoff Frequencies. *J.Appl.Biomech*. 2003; 19(2):178–184. doi:10.1123/jab.19.2.178
34. Clarke T, Frederick E, Cooper L. Effects of shoe cushioning upon ground reaction forces in running. *Int J Sports Med*. 1983; 04(04):247–251. doi:10.1055/s-2008-1026043
35. R Core Team (2022). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/
36. Woolson RF. Wilcoxon signed-rank test. *Wiley Encyclopaedia of Clinical Trials*. 2008. doi:10.1002/9780471462422.eoct979
37. Kawalek JC, Gobet F. Expertise in Contemporary Dance: The Roles of Cognition, Talent, and Deliberate Practice. *J Dance Educ*. 2022; 24(1):21–34. doi:10.1080/15290824.2021.1988089

**Tables**

**Table 1: List of Lower Limb Markers**

|  |  |
| --- | --- |
| Short Name | Full Name |
| **R\_ASI** | Right Anterior Superior Iliac Spine |
| **L\_ASI** | Left Anterior Superior Iliac Spine |
| **R\_PSI** | Right Posterior Superior Iliac Spine |
| **L\_PSI** | Left Posterior Superior Iliac Spine |
| **R\_IC** | Right Iliac Crest |
| **L\_IC** | Left Iliac Crest |
| **R\_GT** | Right Greater Trochanter |
| **L\_GT** | Left Greater Trochanter |
| **R\_TH\_PROX** | Right Thigh Proximal |
| **R\_TH\_DIST** | Right Thigh Distal |
| **R\_TH\_POST** | Right Thigh Posterior |
| **L\_TH\_PROX** | Left Thigh Proximal |
| **L\_TH\_DIST** | Left Thigh Distal |
| **L\_TH\_POST** | Left Thigh Posterior |
| **R\_FEM\_LAT** | Right Lateral Femoral Epicondyle++ |
| **R\_FEM\_MED** | Right Medial Femoral Epicondyle |
| **L\_FEM\_MED** | Left Lateral Femoral Epicondyle++ |
| **L\_FEM\_MED** | Left Medial Femoral Epicondyle |
| **R\_SH\_PROX** | Right Shank Proximal |
| **R\_SH\_DIST** | Right Shank Distal |
| **R\_SH\_POST** | Right Shank Posterior |
| **L\_SH\_PROX** | Left Shank Proximal |
| **L\_SH\_DIST** | Left Shank Distal |
| **L\_SH\_POST** | Left Shank Posterior |
| **R\_MAL\_LAT** | Right Lateral Malleolus++ |
| **R\_MAL\_MED** | Right Medial Malleolus |
| **L\_MAL\_LAT** | Left Lateral Malleolus++ |
| **L\_MAL\_MED** | Left Medial Malleolus |
| **R\_CAL** | Right Calcaneus |
| **R\_5MET** | Right Head of 5th Metatarsal+ |
| **R\_2MET** | Right Head of 2nd Metatarsal+ |
| **L\_CAL** | Left Calcaneus |
| **L\_5MET** | Left Head of 5th Metatarsal+ |
| **L\_2MET** | Left Head of 2nd Metatarsal+ |

+Markers were removed after static calibration trial. ++ The lateral femoral epicondyle and lateral malleolus markers were removed from the landing leg.

**Table 2:** Kinematic and kinetic data for variables during landing phase (means ± SD)

|  |  |
| --- | --- |
| Measured Variable | Pre Intervention Post Intervention |
| Flight Time (s) | 0.32 ± 0.14 | 0.38 ± 0.15\* |
| Jump Height (m) | 0.90 ± 0.10 | 0.95 ± 0.09\* |
| Peak vGRF at Foot Impact (N) | 366.9 ± 205.9 | 368.8 ± 175.5 |
| Normalised Foot Impact peak vGRF (BW) | 0.60 ± 0.31 | 0.60 ± 0.26 |
| Peak vGRF at Knee Impact (N) | 2581.9 ± 467.7 | 2701.6 ± 769.1 |
| Normalised Knee Impact peak vGRF (BW) | 4.22 ± 0.74 | 4.39 ± 1.07 |
| Time to peak Knee Impact vGRF (s) | 0.12 ± 0.03 | 0.14 ± 0.03 |
| Loading Rate to Knee Impact Peak (BW/s) | 38.1 ± 14.7 | 35.8 ± 14.8 |

\*Significant difference p < 0.05

vGRF: vertical Ground Reaction Force

**Figure Legends:**

**Figures 1a to 1e.** Visual representation of the phases of the movement studied.

**Figure 2**. A representative vGRF trace during the knee-drop landing.