The association of range of motion, lower limb strength, and load during jump landings in professional ballet dancers

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ABSTRACT

This study aimed to investigate the associations between peak plantarflexion ankle joint moments and vertical ground reaction forces (vGRF) during jump landings, and static ankle dorsiflexion range of motion (ROM), three-dimensional ankle excursions, and lower extremity strength in professional ballet dancers. Twenty-seven professional ballet dancers volunteered to participate (men = 14, women = 13). Participants attended one data collection session to measure dorsiflexion ROM and isometric lower extremity strength. Two further sessions were used to establish ankle mechanics and vGRFs during countermovement jump landings in seven foot positions, via a seven-camera motion capture system and piezoelectric force platform. Two linear mixed-effects models were used to investigate associations between the target variables and strength, dorsiflexion ROM, and ankle excursions. Dancer identification, sex, and foot position were entered as random effects. Model fit, when considered independent of random effects, was generally poor with the predictor variables explaining little of the variance of peak plantarflexion ankle joint moments ($R^2 = 0.02$) or vGRF ($R^2 = 0.01$). Model fit improved when random effects were considered ($R^2 = 0.65$ & 0.34). Frontal plane ankle excursion was the only predictor variable with a significant negative association with peak plantarflexion ankle joint moments ($p = .016$), although coefficient estimates were small. Strength, static ankle dorsiflexion ROM, and three-dimensional ankle excursions are poor predictors of load experienced at a joint and system level in professional ballet dancers. Differences between individuals, sex, and foot position may be better indicators of the load experienced during jump landings.

Keywords: Biomechanics, Kinematics, Kinetics, Dorsiflexion, Isometric Force

INTRODUCTION

Investigating the athletic demands of professional ballet will better inform training prescription in the context of performance and injury [1]. To that end, professional ballet training is characterised by a high volume of *pliés*, leg raises, jumps, and partner lifts [2]. Jumping is one area that has received attention [3], due to the associated injury risk [4,5]. Jumping was recorded as the inciting event in 38% and 27% of time-loss injuries in professional male and female ballet dancers [5]. The distal lower extremity—collectively the foot, ankle, and shank—incur the greatest burden of injury [5]. Specifically, traumatic lateral ankle sprains and overuse bony stress fractures and stress responses are the most common jump-related injuries [5]. Subsequently, more emphasis is being placed on the biomechanics of jumping in ballet with a particular focus on the distal lower extremities [3,6].

It is well documented from laboratory case reports that the global biomechanics of a lateral ankle sprain is typically associated with excessive plantarflexion and inversion when moving or landing from a jump [7–10]. It can be more challenging, however, to identify the contributing factors to an injury with an insidious onset, such as bony stress fractures or stress responses. The interaction between load exposure, tissue damage, and tissue adaptation is complex and challenging to measure [11–14]. Edwards [13], suggested that cyclic loading of biological tissue—such as a high frequency of jumping on cortical bone properties—can result in tissue failure consistent with a mechanical fatigue process. Further, an increase in the magnitude of load that biological tissue is exposed to is not proportionally linear to the damage that the tissue experiences, such that higher loads cause disproportionally more damage compared to lower loads [12,13]. Thus, understanding the moderators of load magnitude during jumping and landing may reveal specific physical qualities that are associated with lower tissue damage during jumping which might be screened to facilitate targeted interventions.

Lower extremity strength may be clinically meaningful when interpreting lower extremity joint mechanics during landing, as greater strength affords more movement opportunities such that a dancer (or athlete) is able to modulate the degree of joint stiffness upon landing [15]. The ability to modulate joint stiffness upon landing can directly influence the load experienced by the lower extremity, where stiff landings results in higher peak forces and compliant landings result in lower peak forces [16,17]. Lower extremity strength is only one potential moderator when considering a dancer's biomechanics on landing. Howe et al. [18], for example, demonstrated that both strength and mobility—specifically ankle dorsiflexion range of motion (ROM)—should be considered when assessing how landing strategies might moderate peak forces. Ankle dorsiflexion ROM can directly influence the movement affordances available to the ankle and knee throughout the landing phase of a jump, facilitating more compliant landings, and potentially reducing peak forces [19].

This study aimed to investigate the associations between peak ankle joint moments and vertical ground reaction forces (vGRF) during jump landings and static ankle dorsiflexion ROM, three-dimensional ankle excursions, and unilateral isometric lower extremity strength in professional ballet dancers.

METHODS

STUDY DESIGN

A cross-sectional study design was employed to investigate the determinants of peak plantarflexion ankle joint moments and vGRF during jump landings in professional ballet dancers. Participants attended three data collection sessions in a randomised order, separated by 13.5 ± 20.6 days. One session was used to establish maximum strength and range of motion of the lower extremity. Maximum strength was established using unilateral variations of maximal isometric force tests across the squat, standing plantarflexion, and seated plantarflexion positions [22]. Static ankle dorsiflexion ROM was established during a weight-bearing lunge test [23]. Two sessions were used to establish ankle mechanics and vGRF variables during countermovement jumps in seven different foot positions (Figure 1). All testing was conducted in the Royal Opera House, UK.

PARTICIPANTS

A sample of 27 professional ballet dancers volunteered to participate in this research (men: n = 14, age: 26.7 ± 4.9 y, height: 1.79 ± 0.04 m, mass: 72.6 ± 5.2 kg; women: n = 13, age: 24.0 ± 3.7 y, height: 1.68 ± 0.04 m, mass: 55.2 ± 3.3 kg). Participants were required to be injury free and have not sustained a time-loss injury in the six weeks prior to data collection. Written informed consent was provided by all participants and ethical approval was granted by St Mary’s University Ethics Committee, in accordance with the Declaration of Helsinki.

PROCEDURE

Isometric Force and Weight-Bearing Lunge Testing

Following a progressive and standardised warm-up participants performed three five-second maximal isometric contractions on the right limb during a unilateral squat, unilateral standing plantarflexion, and unilateral seated plantarflexion test [22]. A twenty-second inter-repetition and a two-minute inter-set recovery were provided.

The vGRF data were collected using a force platform incorporating 4 strain gauge load cells (MUSCLELAB, Ergotest Innovation AS, Stathelle, Norway) sampling at 1000 Hz. An isometric rig, with 2.5 cm adjustable vertical spacing, and a barbell (Sportesse, Somerset, United Kingdom) were used for all tests, with a 3.3 cm thick foam pad (Power Guidance, London, England) around the barbell for comfort. Bodyweight was calculated from a five-second static trial where participants were standing motionless on the force platform. Participants were required to wear their own shoes during testing. Participants were instructed to “push maximally into the barbell” before each trial. Each trial was initiated by the researcher instructing the participant to adopt the relevant position and then counting down “3, 2, 1, Push”. The force platform was zeroed prior to each set. A detailed outline of each of the isometric force tests conducted is described elsewhere [22].

Three weight-bearing lunge tests were completed with each participant. The maximum shin angle during each weight-bearing lunge test was recorded using an inclinometer (Acumar Digital Inclinometer, Lafayette Instrument Company, Indiana, USA). A detailed overview of the testing procedure is described elsewhere [23].

Jump Testing

Participants completed a standardised and progressive warm-up prior to testing. Retroreflective markers (22 mm diameter) were attached to the right: greater trochanter, medial and lateral joint lines of the knee, medial and lateral malleolus, posterior aspect of the calcaneus, superior aspect of the navicular, medial aspect of the 1st metatarsal head, and the lateral aspect of the 5th metatarsal head using double-sided adhesive tape and adhesive spray. A curved rigid moulded cluster with four retroreflective markers was attached to the lateral aspect of the right shank using cohesive elastic tape and electrical tape (Figure 2).

Participants completed five maximal bilateral countermovement jumps across seven different foot positions during one data collection session. These positions included parallel, first, second, fourth with the front foot on the force platform, fourth with the back foot on the force platform, fifth with the front foot on the force platform, and fifth with the back foot on the force platform (Figure 1). Foot positions were grouped based on their biomechanical profile during jump landings (parallel, grouped first and second position, grouped front foot, and grouped back foot). Participants also completed five maximal bilateral countermovement jumps across parallel and first positions during a separate data collection session. The reliability of ankle mechanics and vGRF measures during jump landings in professional ballet dancers are presented elsewhere [24].

Prior to jumping, the right limb was positioned on the force platform and the left limb was positioned on a wooden frame that surrounded the force platform (Figure 1). The participant's hands were placed on their shoulders for all jumps. Order effects were mitigated by alternating jumps until one jump in each foot position was performed within a set. Twenty seconds of inter-rep rest and two minutes of inter-set rest were provided [25].

A seven-camera motion capture system (MX3/MX3+, Vicon Motion Systems Ltd, Oxford, United Kingdom) sampling at 200 Hz, and one piezoelectric force platform (9268A, Kistler, Winterthur, Switzerland) sampling at 1000 Hz synchronously recorded retroreflective marker coordinates and ground reaction forces, respectively. The global coordinate system was defined such that Z was vertical, X was mediolateral, and Y was the cross-product of Z and X.

DATA ANALYSIS

Isometric Force and Weight-Bearing Lunge Testing

Peak vGRF was extracted following maximal isometric trials directly from the force platform software and no filtering was applied. Mean vGRF was extracted from static bodyweight trials and used to calculate vGRF relative to body weight. The mean ± standard deviation (SD) of the relative vGRF was then calculated for each position. The mean ± SD of peak shin angle during the three weight-bearing lunge trials was calculated as a measure of static ankle dorsiflexion ROM.

Jump Testing

Marker trajectories were reconstructed and labelled in Vicon Nexus (Vicon Motion Systems Ltd, Oxford, United Kingdom) before being processed in Visual 3D (v2021.113 C-Motion©, USA). All marker trajectory gaps consisted of seven frames or fewer and were interpolated using cubic splines. A foot and a shank segment were created in Visual 3D. The foot was defined by the medial and lateral malleolus as the proximal endpoints and the medial aspect of the 1st metatarsal head and the lateral aspect of the 5th metatarsal head as the distal endpoints. The shank was defined by the medial and lateral joint lines of the knee as the proximal endpoints and the medial and lateral malleolus as the distal endpoints. Foot and shank segment inertia parameters were defined in line with de Leva [26]. Individual and cluster markers for the foot and shank were used to track segments during dynamic trials. Marker and ground reaction force data were filtered at 8 Hz using a low-pass fourth-order Butterworth filter, determined via residual analysis [27]. An inverse kinematics approach was used to estimate the pose of the segments [28], allowing three degrees of rotation but no translation between the foot and shank segments. Ankle joint angles were calculated using an XYZ Cardan rotation sequence. Kinematic data and segmental inertial data were combined with ground reaction force data to calculate plantarflexion ankle joint moment using inverse dynamics with the shank segment used as both the reference segment and the resolution coordinate system [26]. Ankle joint moment was normalised for comparisons between participants [29]—leg length was replaced with height [30]:

$$Normalised\ Ankle\ Moment = \frac{Moment}{mgh}$$

Vertical ground reaction force data were reprocessed and filtered at 250 Hz using a low pass fourth-order Butterworth filter, determined via residual analysis [27], to calculate normalised vGRF:

$$Normalised\ vGRF = \frac{vGRF}{mg}$$

Vertical displacement—hereon referred to as jump height—was calculated as the difference between the height of the greater trochanter in standing and at the peak of flight using the raw marker coordinates.

The landing phase of each jump was extracted; the start of the trial was identified by the point of initial contact following a period of flight where vGRF was > 50 N and the end of the trial was identified by the point at which data collection ceased. Peak values of ankle mechanics and vGRF measures were then calculated through all planes of motion. Peak ankle joint moment and peak landing vGRF were normalised to jump height [31]. Three-dimensional ankle excursions were calculated by subtracting the minimum ankle angle from the peak ankle angle across each plane of motion.

STATISTICAL ANALYSIS

Two linear mixed-effects models were constructed using the R package *lme4* [32]. The first model was to establish associations between peak plantarflexion ankle joint moment and dancer strength (squat, standing plantarflexion, and seated plantarflexion isometric force tests), static ankle dorsiflexion ROM (weight-bearing lunge test), and three-dimensional ankle excursions. The second model was to establish associations between peak vGRF and the aforementioned predictor variables. For both models, strength, static ankle dorsiflexion ROM, and three-dimensional ankle excursions were entered as fixed effects and the dancer's unique identification, sex, and grouped foot position were entered as random effects. All numeric data were scaled using the R *base* package before models were computed [33]. An alpha level of $p < .025$ was set to account for the multiplicity of two outcome variables. Model goodness-of-fit was assessed via a marginal (fixed effects only) and conditional (both fixed and random effects) R^2 value using the R package *MuMIn* [34]. Normality, linearity, homoscedasticity, and independence of residuals were confirmed for both models. The second model demonstrated a non-normal distribution of residuals, however, linear mixed-effects models are robust to violations of normality, and thus no transformation was applied [35]. All data processing and statistical analysis were conducted using R (version 4.2.1, R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Descriptive statistics for static ankle dorsiflexion ROM and unilateral isometric lower extremity strength are presented in Table 1. Six jumps were corrupt and unable to be processed and a further six jumps were identified as extreme outliers and subsequently removed (n = 12; 0.8%), as such a total of 1338 jumps were included in the analysis.

The linear mixed effects model investigating factors associated with peak plantarflexion ankle joint moment revealed a significant main effect of frontal plane ankle excursion (p = .016), however, coefficient estimates were negligible, such that a one-unit increase in the predictor variable was associated with a 0.000009 decrease in frontal plane ankle excursions. No significant main effects were observed for isometric squat strength (p = .301), isometric standing plantarflexion strength (p = .653), isometric seated plantarflexion strength (p = .366), static ankle dorsiflexion ROM (p = .850), or sagittal (p = .621) and transverse (p = . 597) plane ankle excursions. The marginal R^2 value indicated that 2.3% of the variance in peak plantarflexion ankle joint moment was explained by dancer strength, static ankle dorsiflexion ROM, and three-dimensional ankle excursions. Conversely, the conditional R^2 value indicated that 65.5% of the variance in peak plantarflexion ankle joint moment was explained by dancer strength, static ankle dorsiflexion ROM, three-dimensional ankle ROM, dancer's unique identification, sex, and foot position.

The linear mixed effects model investigating factors associated with peak vGRF revealed no significant main effects of any variable (p = .170–.942). The marginal R^2 value indicated that 1.0% of the variance in peak vGRF was explained by dancer strength, static ROM, and ankle excursions. Conversely, the conditional R^2 value indicated that 34.3% of the variance in peak vGRF was explained by dancer strength, static ROM, ankle excursions, dancer's unique identification, sex, and foot position. The coefficient estimates for both models are presented in Figure 3. The raw data for both models are presented in Figures 4 and 5. The raw data illustrating random factors are presented in Figures 6 and 7.

DISCUSSION

This is the first study to investigate the associations between peak plantarflexion ankle joint moments and peak vGRF during jump landings and strength, ROM, and excursions in professional ballet dancers. The results demonstrate that the variables selected as fixed effects (strength, ROM, and excursions) have poor associations with the target variables, with none associated with peak vGRF and only smaller frontal plane ankle excursions being associated with greater peak plantarflexion ankle joint moments. Conversely, the random factors (sex, foot position, and unique dancer identification) were better able to explain the variance in peak plantarflexion ankle joint moments, and, to a lesser degree, peak vGRF.

No significant associations were identified between unilateral isometric lower extremity strength and either of the target variables. Several studies have identified that lower extremity strength characteristics are associated with desirable lower extremity biomechanics—such as dynamic joint alignment, smaller vGRFs, and reduced joint stiffness or moments—during jump landings [15,36–40]. Conversely, others have identified no association between lower extremity strength characteristics and lower limb biomechanics during landing tasks [41–43], one of which has even called for a paradigm shift in the design of injury prevention programs as a consequence [42]. Much of the research that has found associations, however, have focused on the strength characteristics and landing biomechanics of the knee and hip as opposed to the ankle [15,36–40]. Further, several of these studies have selected lower limb kinematics—as opposed to kinetics—as their target variables due to the association between dynamic joint alignment and anterior cruciate ligament injury [38–42]. It is plausible that kinematic associations are present in the absence of kinetic associations in the aforementioned studies. To the authors' knowledge, no previous literature has investigated lower extremity strength and ankle joint moments. Greater ankle plantarflexion strength likely makes a desirable contribution to tissue capacity and dynamic joint stiffness around the ankle; however, it does not appear to predict landing biomechanics.

No associations between static dorsiflexion ROM and the target variables were observed. Mixed findings have been reported in studies in which ankle dorsiflexion has been investigated. Some authors have shown associations between dorsiflexion ROM and landing kinetics [44] or kinematics [19,44], whereas others have not [19,45,46]. Further, some authors have demonstrated joint-level associations (e.g., ankle or knee moments) but not system-level associations (e.g., vGRF) [47] with ankle dorsiflexion ROM. Such conflicting findings have previously been attributed to differences in movement strategies, where compensations in frontal and transverse planes of motion have facilitated more compliant landings in individuals with reduced dorsiflexion range of motion [48]. The reference data we provide, however, suggest that all professional ballet dancers had high degrees of ankle dorsiflexion when compared to the participants in similar research [44,46,47], although differences in assessment methods were noted in two of the three studies. We speculate that there may be an interaction effect between strength and static ankle dorsiflexion ROM that modulates joint stiffness and dynamic joint alignment.

We observed associations between frontal plane ankle excursion and peak plantarflexion ankle joint moments, such that smaller frontal plane ankle excursions may be indicative of larger plantarflexion joint moments. In line with previous authors, frontal (or transverse) plane excursions may manifest where additional ankle ROM is desired or a lack of dynamic joint alignment is present [48]. It should be noted, however, that the model fit was poor and the coefficient estimates, indicative of effect size, were small. To that end, practitioners working within dance should interpret these findings with caution.

The fixed effects selected in the present study resulted in a poor fit across both models when considered independent of the random effects. When the random effects were accounted for, however, both models' fit improved, although peak vGRF was to a lesser degree. As such, dancer strength, static ankle dorsiflexion ROM, and three-dimensional ankle excursions are poor predictors of the load experienced by the ankle and system during jump landings in professional ballet dancers. Dancer sex, jump position, and individual variation are more suitable variables to consider when assessing whether a dancer will be exposed to greater or lesser magnitudes of load during jump landings. It should be noted that the lack of association between strength and ROM and the target variables does not indicate that these physical qualities are not important to increase injury resilience [48–51]. Future work may wish to prospectively investigate whether these variables (strength, static ROM, and ankle excursions) increase dancer resilience to injury (i.e., by increasing tissue capacity) as opposed to using them to predict the peak load experienced at a joint and a system level.

STRENGTHS AND LIMITATIONS

Previous work is sparse pertaining to male and professional ballet dancers [3], and, thus, the present study offers new insights for practitioners. A limitation, however, is that only the right limb was measured during bilateral jumps; investigating the entire kinetic chain across both limbs may yield different results. Larger laboratories with additional cameras may facilitate more detailed analyses. To that end, there are logistical challenges associated with applied research within a professional ballet company due to dense rehearsal schedules which limit time and space [52]. Future work may benefit from permanent laboratories that are established within the residence of professional companies. The present study included maximum isometric strength as a predictor variable, other muscle contractions (such as isotonic or isokinetic) may yield different results.

PRACTICAL APPLICATIONS

The model goodness-of-fit, when considered independent of random effects, was generally poor. As such, practitioners working with professional ballet dancers should be aware that isometric strength, dorsiflexion ROM, and ankle excursions will not indicate the magnitudes of load experienced at the ankle joint or a system level during jump landings. Nevertheless, isometric strength, dorsiflexion ROM and ankle excursions are likely important factors to consider in the context of injury [48–51]. Dancer sex, foot position, and individual variation are more appropriate factors to consider when assessing the load experienced at a joint or system level. To that end, regular physical profiling, appropriate load management, and individualised training programs are likely important to minimise injury risk. This study also provides reference data relating to isometric strength and dorsiflexion ROM in professional ballet dancers.

CONCLUSION

To the authors' knowledge, this is the first study to investigate the associations between peak ankle plantarflexion joint moment and peak vGRF, and dorsiflexion ROM, ankle excursions, and isometric strength during jump landings in professional ballet dancers. The predictor variables did not explain the variance in the target variables well and practitioners should be aware of this when interpreting physical profiling data. Future work may wish to prospectively investigate the complex relationship between load exposure, tissue tolerance, and injury.

REFERENCES

1. Escobar Álvarez JA, Fuentes García J, Da Conceição F, Jiménez-Reyes P. Individualized training based on force–velocity profiling during jumping in ballet dancers. Int J Sports Physiol Perform. 2019;1–7.

2. Shaw JW, Mattiussi AM, Brown DD, Springham M, Pedlar CR, Tallent J. The activity demands and physiological responses observed in professional ballet: A systematic review. J Sport Exerc Sci. 2021;5:254–69.

3. Mattiussi A, Shaw JW, Brown DD, Price P, Cohen DD, Pedlar CR, et al. Jumping in ballet: A systematic review of kinetic and kinematic parameters. Med Probl Perform Art. 2021;36:108–28.

4. Allen N, Nevill A, Brooks J, Koutedakis Y, Wyon M. Ballet injuries: Injury incidence and severity over 1 year. J Orthop Sports Phys Ther. 2012;42:781–90.

5. Mattiussi A, Shaw J, Williams S, Price P, Brown D, Cohen D, et al. Injury epidemiology in professional ballet: a five-season prospective study of 1596 medical attention injuries and 543 time-loss injuries. Br J Sports Med. 2021;bjsports-2020-103817.

6. Wyon MA, Twitchett E, Angioi M, Clarke F, Metsios G, Koutedakis Y. Time motion and video analysis of classical ballet and contemporary dance performance. Int J Sports Med. 2011;32:851–5.

7. Fong DTP, Hong Y, Shima Y, Krosshaug T, Yung PSH, Chan KM. Biomechanics of supination ankle sprain: A case report of an accidental injury event in the laboratory. Am J Sports Med. 2009;37:822–7.

8. Gehring D, Wissler S, Mornieux G, Gollhofer A. How to sprain your ankle - a biomechanical case report of an inversion trauma. J Biomech [Internet]. Elsevier; 2013;46:175–8. Available from: http://dx.doi.org/10.1016/j.jbiomech.2012.09.016

9. Terada M, Gribble PA. Jump landing biomechanics during a laboratory recorded recurrent ankle sprain. Foot Ankle Int. 2015;36:842–8.

10. Kristianslund E, Bahr R, Krosshaug T. Kinematics and kinetics of an accidental lateral ankle sprain. J Biomech [Internet]. Elsevier; 2011;44:2576–8. Available from: http://dx.doi.org/10.1016/j.jbiomech.2011.07.014

11. Ng JL, Kersh ME, Kilbreath S, Knothe Tate M. Establishing the basis for mechanobiology-based physical therapy protocols to potentiate cellular healing and tissue regeneration. Front Physiol. 2017;8:1–13.

12. Kalkhoven JT, Watsford ML, Coutts AJ, Edwards WB, Impellizzeri FM. Training load and injury: Causal pathways and future directions. Sport Med [Internet]. Springer International Publishing; 2021;51:1137–50. Available from: https://doi.org/10.1007/s40279-020-01413-6

13. Edwards WB. Modeling Overuse Injuries in Sport as a Mechanical Fatigue Phenomenon. Exerc Sport Sci Rev. 2018;46:224–31.

14. Bahr R, Krosshaug T. Understanding injury mechanisms: A key component of preventing

injuries in sport. Br J Sports Med. 2005;39:324–9.

15. Schmitz RJ, Shultz SJ. Contribution of knee flexor and extensor strength on sex-specific energy absorption and torsional joint stiffness during drop jumping. J Athl Train. 2010;45:445–52.

16. Myers CA, Torry MR, Peterson DS, Shelburne KB, Giphart JE, Krong JP, et al. Measurements of tibiofemoral kinematics during soft and stiff drop landings using biplane fluoroscopy. Am J Sports Med. 2011;39:1714–22.

17. You CH, Huang CH. Effects of leg stiffness regulated by different landing styles on vertical drop jump performance. J Hum Kinet. 2022;83:29–37.

18. Howe LP, Bampouras TM, North JS, Waldron M. Improved ankle mobility after a 4-week training program affects landing mechanics: A randomized controlled trial. J Strength Cond Res [Internet]. 2022;36:1875–83. Available from: www.nsca.com

19. Howe LP, Bampouras TM, North J, Waldron M. Ankle dorsiflexion range of motion is associated with kinematic but not kinetic variables related to bilateral drop-landing performance at various drop heights. Hum Mov Sci [Internet]. Elsevier; 2019;64:320–8. Available from: https://doi.org/10.1016/j.humov.2019.02.016

20. Moran LR, Hegedus EJ, Bleakley CM, Taylor JB. Jump load: Capturing the next great injury analytic. Br J Sports Med. 2019;53:8–9.

21. Bittencourt NFN, Meeuwisse WH, Mendonça LD, Nettel-Aguirre A, Ocarino JM, Fonseca ST. Complex systems approach for sports injuries: Moving from risk factor identification to injury pattern recognition - Narrative review and new concept. Br J Sports Med. 2016;50:1309–14.

22. Mattiussi AM, Shaw JW, Cohen DD, Price P, Brown DD, Charles R, et al. Reliability , variability , and minimal detectable change of bilateral and unilateral lower extremity isometric force tests. J Sport Exerc Sci. 2022;6:191–9.

23. Konor MM, Morton S, Eckerson JM, Grindstaff TL. Reliability of three measures of ankle dorsiflexion range of motion. Int J Sports Phys Ther [Internet]. 2012;7:279–87. Available from: http://www.ncbi.nlm.nih.gov/pubmed/22666642%0Ahttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC3362988

24. Mattiussi AM, Shaw JW, Price P, Brown DD, Cohen DD, Lineham J, et al. Reliability of Ankle Mechanics During Jump Landings in Turned-Out and Parallel Foot Positions in Professional Ballet Dancers. J Biomech [Internet]. 2023;In press:111662. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0021929023002312

25. Pereira G, Almeida AG, Rodacki ALF, Ugrinowitsch C, Fowler NE, Kokubun E. The influence of resting period length on jumping performance. J Strength Cond Res. 2008;22:1259–64.

26. de Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J Biomech. 1996;29:1223–30.

27. Winter DA. Biomechanics and Motor Control of Human Movement [Internet]. Fourth Edi.

Biomech. Mot. Control Hum. Mov. Fourth Ed. Hoboken, NJ, USA: John Wiley & Sons, Inc.; 2009. Available from: http://doi.wiley.com/10.1002/9780470549148

28. Lu TW, O'Connor JJ. Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. J Biomech. 1999;32:129–34.

29. Hof AL. Scaling gait data to body size. Gait Posture. 1996;4:222–3.

30. Atack AC, Trewartha G, Bezodis NE. A joint kinetic analysis of rugby place kicking technique to understand why kickers achieve different performance outcomes. J Biomech. 2019;87:114–9.

31. Mesisca JK, Peebles AT, Queen RM. Including jump height when normalizing single hop impact kinetics can change the directionality of findings. Clin Biomech [Internet]. Elsevier Ltd; 2021;88:105443. Available from: https://doi.org/10.1016/j.clinbiomech.2021.105443

32. Bates D, Mächler M, Bolker BM, Walker SC. Fitting linear mixed-effects models using lme4. J Stat Softw. 2015;67:1–48.

33. R Core Team. R: A language and environment for statistical computing [Internet]. Vienna, Austria; 2022. Available from: https://www.r-project.org/

34. Bartoń K. MuMIn: Multi-Model Inference [Internet]. 2023. Available from: https://cran.r-project.org/package=MuMIn

35. Schielzeth H, Dingemanse NJ, Nakagawa S, Westneat DF, Allegue H, Teplitsky C, et al. Robustness of linear mixed-effects models to violations of distributional assumptions. Methods Ecol Evol. 2020;11:1141–52.

36. Malloy P, Morgan A, Meinerz C, Christopher F, Kipp K. Hip external rotator strength is associated with better dynamic control of the lower extremity during landing tasks. J Strength Cond Res. 2017;30:282–91.

37. Montgomery MM, Shultz SJ, Schmitz RJ, Wideman L, Henson RA. Influence of lean body mass and strength on landing energetics. Med Sci Sports Exerc. 2012;2376–83.

38. Nagai T, Sell TC, House AJ, Abt JP, Lephart SM. Knee proprioception and strength and landing kinematics during a single-leg stop-jump task. J Athl Train. 2013;48:31–8.

39. Bittencourt NFN, Ocarino JM, Mendonça LD, Hewett TE, Fonseca ST. Foot and Hip Contributions to High Frontal Plane Knee Projection Angle in Athletes: A Classification and Regression Tree Approach. J Orthop Sport Phys Ther [Internet]. 2012;42:996–1004. Available from: http://www.jospt.org/doi/10.2519/jospt.2012.4041

40. Howard JS, Fazio MA, Carl G, Uhl TL, Jacobs CA. Structure, sex, and strength and knee and hip kinematics during landing. J Athl Train. 2011;46:376–85.

41. Mccann RS, Terada M, Kosik KB, Gribble PA. Landing kinematics and isometric hip strength of individuals with chronic ankle instability. Foot Ankle Int. 2019;40:969–977.

42. Beutler AI, Motte SJ De, Marshall SW, Padua DA, Barry P. Muscle strength and qualitative jump-landing differences in male and female military cadets: The jump-ACL study. J Sport Sci

Med. 2009;8:663–71.

43. Mizner RL, Kawaguchi JK, Chmielewski TL. Muscle Strength in the Lower Extremity Does Not Predict Postinstruction Improvements in the Landing Patterns of Female Athletes. J Orthop Sport Phys Ther [Internet]. 2008;38:353–61. Available from: http://www.jospt.org/doi/10.2519/jospt.2008.2726

44. Fong CM, Blackburn JT, Norcross MF, McGrath M, Padua DA. Ankle-dorsiflexion range of motion and landing biomechanics. J Athl Train. 2011;46:5–10.

45. Whitting JW, Steele JR, McGhee DE, Munro BJ. Dorsiflexion capacity affects Achilles tendon loading during drop landings. Med Sci Sports Exerc. 2011;43:706–13.

46. Whitting JW, Steele JR, McGhee DE, Munro BJ. Effects of passive ankle dorsiflexion stiffness on ankle mechanics during drop landings. J Sci Med Sport [Internet]. Sports Medicine Australia; 2012;15:468–73. Available from: http://dx.doi.org/10.1016/j.jsams.2012.03.004

47. Malloy P, Morgan A, Meinerz C, Geiser C, Kipp K. The association of dorsiflexion flexibility on knee kinematics and kinetics during a drop vertical jump in healthy female athletes. Knee Surgery, Sport Traumatol Arthrosc. 2015;23:3550–5.

48. Mason-Mackay AR, Whatman C, Reid D. The effect of reduced ankle dorsiflexion on lower extremity mechanics during landing: A systematic review. J Sci Med Sport [Internet]. Sports Medicine Australia; 2017;20:451–8. Available from: http://dx.doi.org/10.1016/j.jsams.2015.06.006

49. Hrysomallis C. Neck muscular strength, training, performance and Sport injury risk: A review. Sport Med. Springer International Publishing; 2016;46:1111–24.

50. De La Motte SJ, Gribbin TC, Lisman P, Murphy K, Deuster PA. Systematic review of the association between physical fitness and musculoskeletal injury risk: Part 2 — Muscular endurance and muscular strength. J Strength Cond Res. 2017;31:3218–34.

51. de la Motte SJ, Lisman P, Gribbin TC, Murphy K, Deuster PA. Systematic Review of the Association Between Physical Fitness and Musculoskeletal Injury Risk: Part 3—Flexibility, Power, Speed, Balance, and Agility. J Strength Cond Res [Internet]. 2019;33:1723–35. Available from: https://journals.lww.com/00124278-201906000-00031

52. Shaw JW, Mattiussi AM, Brown DD, Williams S, Springham M, Pedlar CR, et al. Rehearsal and Performance Volume in Professional Ballet: A Five-Season Cohort Study. J Danc Med Sci. 2022;

TABLE 1

Table 1. Mean ± 1 standard deviation for static dorsiflexion range of motion and unilateral isometric force tests.

Sex	*n*	Dorsiflexion ROM (°)	SL Isometric Squat (N/N)	SL Isometric Standing PF (N/N)	SL Isometric Seated PF (N/N)
Female	13	49.9 ± 4.5	3.1 ± 0.3	2.8 ± 0.2	1.8 ± 0.3
Male	14	46.0 ± 3.3	3.7 ± 0.4	3.0 ± 0.3	1.8 ± 0.2

ROM, range of motion; SL, single leg; PF, plantarflexion

FIGURE 1

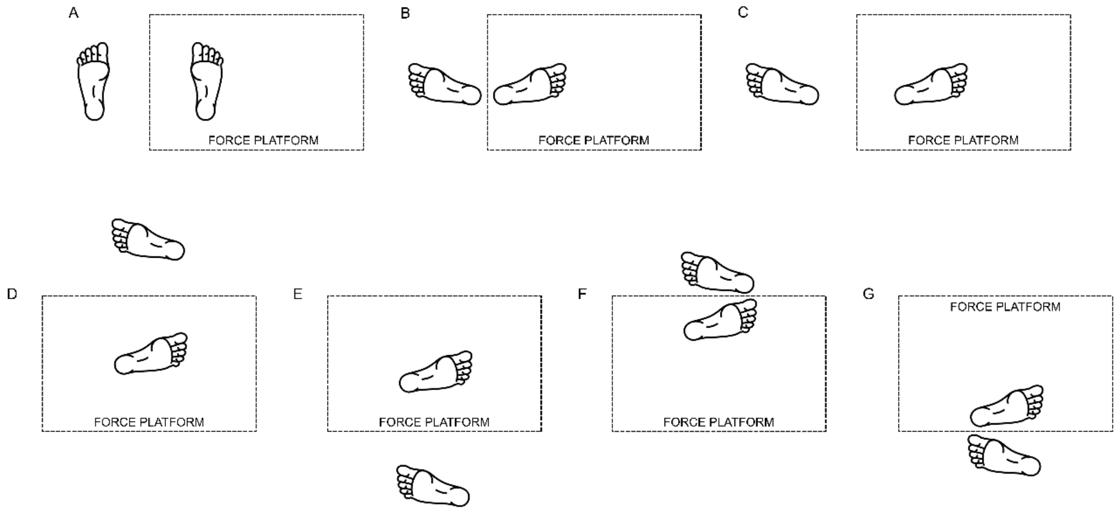

Figure 1. The foot positions tested in the present study with reference to the force platform. (A) parallel, (B) first, (C) second, (D) fourth back, (E) fourth front, (F) fifth back, (G) fifth front. Grouped first and second position indicates that all jumps depicted in (B) and (C) were grouped; Grouped front foot position indicates that all jumps depicted in (E) and (G) were grouped; Grouped back foot position indicates that all jumps depicted in (D) and (F) were grouped.

FIGURE 2

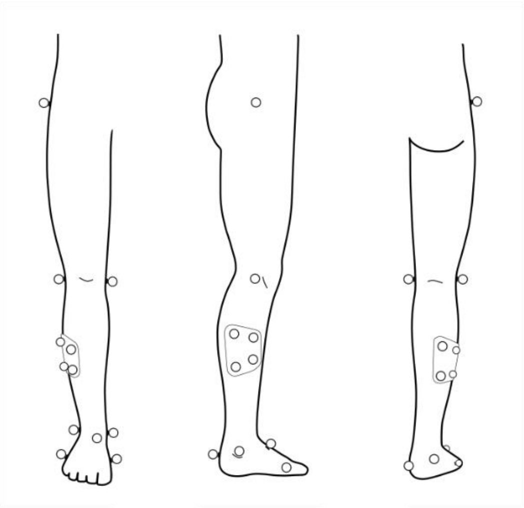

Figure 2. Marker placement on the right limb from the anterior, lateral, and posterior aspects.

FIGURE 3

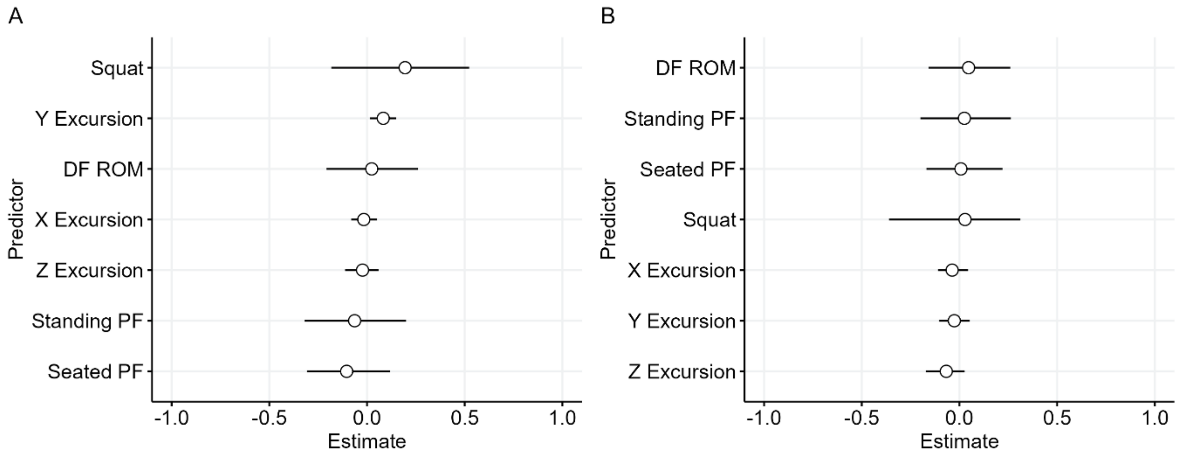

Figure 3. Coefficient estimates and 95% confidence intervals for the linear mixed-effects models investigating (A) peak normalised plantarflexion ankle joint moment and (B) peak normalised vGRF. A positive coefficient estimate indicates that an increase in the predictor value is associated with an increase in the target variable whereas a negative value indicates the opposite. Data are scaled (-1.0–1.0) and not true to their original units to facilitate comparison on a single axis. DF, dorsiflexion; ROM, range of motion; PF, plantarflexion

FIGURE 4

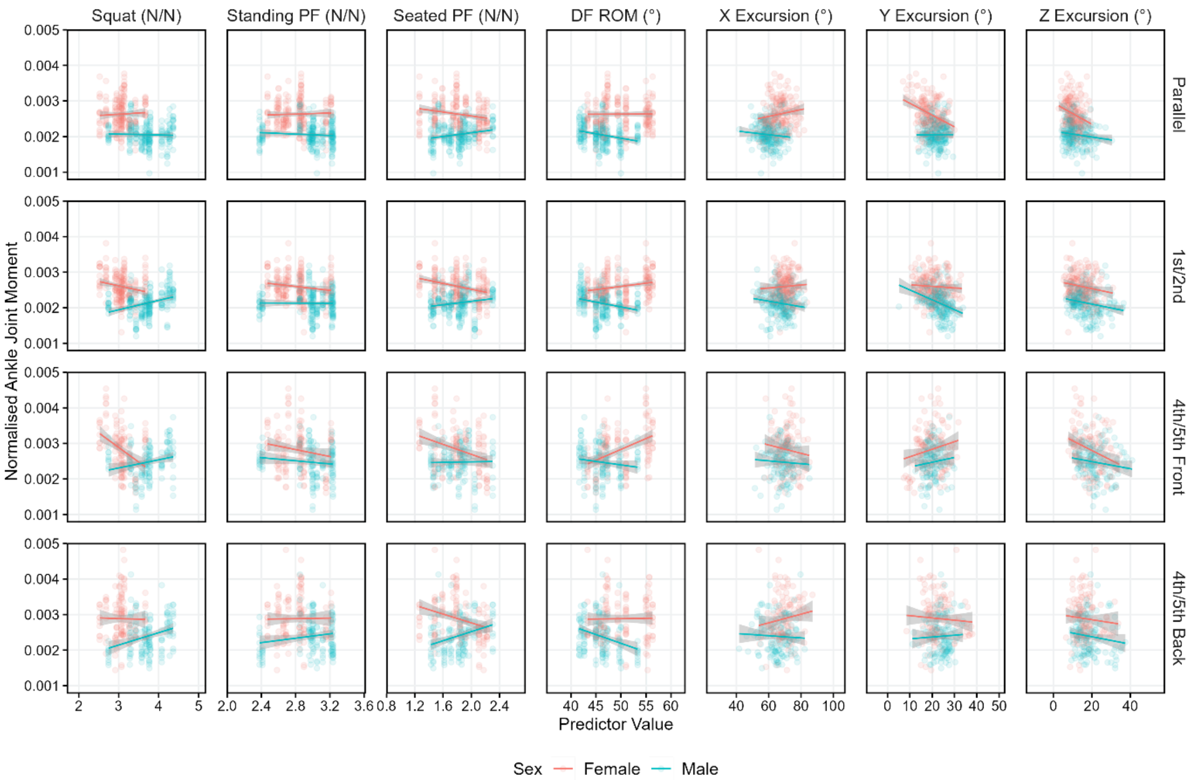

Figure 4. Raw data illustrating the associations between peak normalised plantarflexion ankle joint moment and fixed factors (dancer strength, static ROM, and ankle excursions) accounting for random factors (sex, grouped foot position, and dancers' unique identification). DF, dorsiflexion; ROM, range of motion; PF, plantarflexion

FIGURE 5

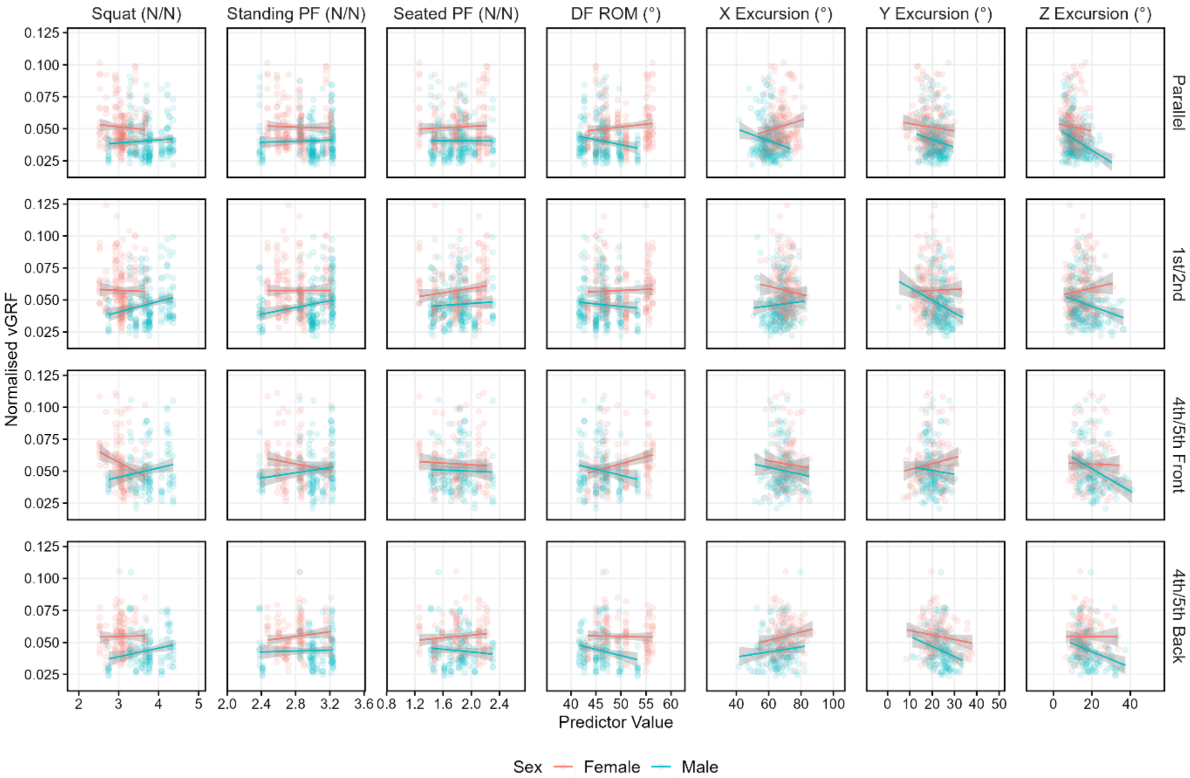

Figure 5. Raw data illustrating the associations between peak normalised vGRF and fixed factors (dancer strength, static ROM, and ankle excursions) accounting for random factors (sex, grouped foot position, and dancers' unique identification). DF, dorsiflexion; ROM, range of motion; PF, plantarflexion

FIGURE 6

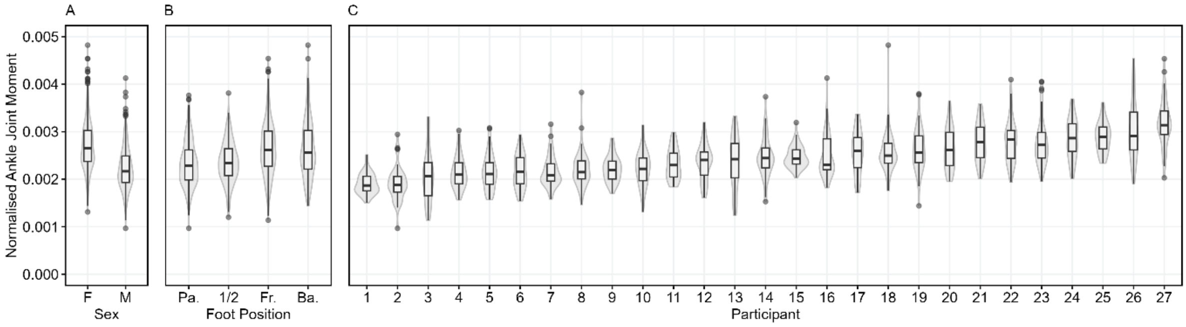

Figure 6. Raw data illustrating the associations between peak normalised plantarflexion ankle joint moment and random factors (sex, grouped foot position, dancers' unique identification). Pa., Parallel; 1/2, first and second; Fr., front foot in fourth and fifth; Ba., back foot in fourth and fifth position

FIGURE 7

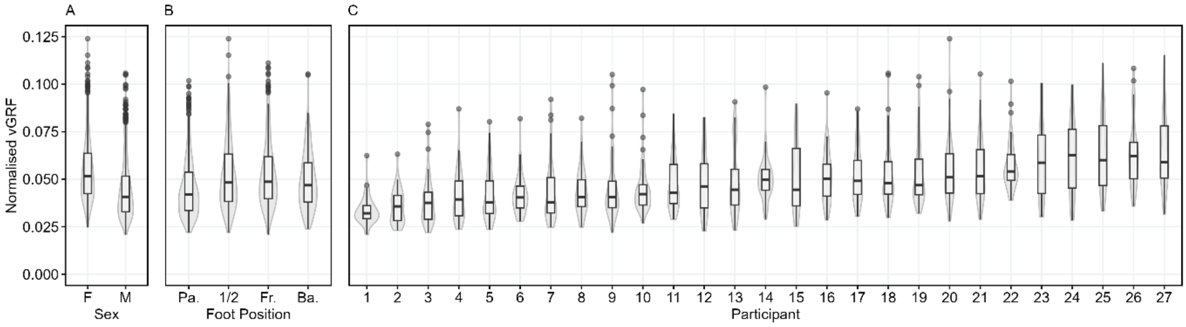

Figure 7. Raw data illustrating the associations between peak normalised vGRF and random factors (sex, grouped foot position, dancers' unique identification). Pa., Parallel; 1/2, first and second; Fr., front foot in fourth and fifth; Ba., back foot in fourth and fifth position