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ABSTRACT

This study aimed to investigate the effect foot position on ankle joint mechanics and vertical ground reaction forces (vGRF) across jump landings in professional ballet dancers. Twenty-seven professional ballet dancers (men: 14; women: 13) attended one data collection session, completing five maximal countermovement jumps in parallel, first, second, fourth, and fifth positions. Three-dimensional ankle mechanics, landing vGRF variables, and jump height were recorded via a seven-camera motion capture system and one force platform. A repeated measures multivariate analysis of variance was used to assess the main effects foot position across all target variables. A linear discriminate analysis was conducted to investigate target variables across foot positions. Frontal and transverse plane ankle mechanics had the largest impact when discriminating between foot positions. Ankle power in the transverse plane during jump landing in fourth was double that of all other positions. Our findings suggest that ankle range of motion should be restored before returning to jumps in fourth and fifth positions following distal lower extremity injury. The multiplanar energy transfer observed indicates a need for specific exercises to develop multiplanar force and rate of force development of local structures around the ankle.

Keywords: Biomechanics, Ground Reaction Forces, Kinematics, Kinetics, Machine Learning

INTRODUCTION

The rehearsal and performance demands of professional ballet are characterised by a high volume of jumping actions (Shaw et al., 2021). Jumping actions have been associated with a third of all medical attention and time-loss injuries in professional ballet dancers (A. M. Mattiussi et al., 2021); with the greatest burden observed around the distal lower extremity. Moran et al. (2019) suggested that landing biomechanics (and jump volume) may provide practitioners with ‘the next great injury analytic’ for activities that have high jumping demands. Indeed, investigations into landing biomechanics will provide insights into the load experienced by different structures of the lower extremity. Once the load experienced during landing is understood, practitioners can better manage the load-capacity relationship in hope of mitigating potential injury risk and maximising performance in ballet dancers (Edwards, 2018).

There is a vast repertoire of jumps to which ballet dancers will be exposed each day, making the documentation of all of them challenging. Different ballet jumps may be characterised by whether they are travelling or stationary; have contributions from a single limb or both limbs; and whether there are technical actions throughout the different phases of the jump (such as beats, splits, or arabesques) (A. Mattiussi et al., 2021). There are, however, codified foot positions that underpin all ballet technique, referred to as first, second, third, fourth, and fifth positions. All jumping actions will take off or land in one of these fundamental foot positions which provides an opportunity to refine the documentation of jumping biomechanics in ballet. To date, only two studies have investigated the effect of these codified foot positions on lower extremity biomechanics during jumping (Imura & Iino, 2017; Ravn et al., 2007).

The technical requirements of ballet change the kinetic and kinematic characteristics of jumping when compared to more typical foot positions (i.e., parallel) (A. Mattiussi et al., 2021). For example, kinematic differences such as minimal hip flexion, an upright torso, and an externally rotated lower limb were observed when jumps in turn out were compared to jumps in parallel (Imura & Iino, 2017). Kinetic variables, such as lower extremity joint moment, power, and work have exhibited a proximal-to-distal shift in joint contributions during ballet-specific jumps compared to traditional jumps (Ravn et al., 2007). All of these characteristics are indicative of greater contributions from the distal lower extremities during jumping actions in ballet dancers, placing a greater demand on the tissues around the foot and ankle. It should be noted, however, that both of the aforementioned studies have only investigated the take-off phase of a jump. Presently there is a lack of data pertaining to distal lower extremity joint mechanics during the landing phase of different ballet jumps.

Where studies have investigated landing biomechanics in ballet dancers peak landing vertical ground reaction force (vGRF) has been the most commonly reported variable (A. Mattiussi et al., 2021). The range in peak landing vGRF is between 1.4–9.6 times body weight (BW) during various unilateral and bilateral ballet-specific jumps (Dworak et al., 2006; Gorwa et al., 2020; Lee et al., 2012; McPherson et al., 2019; Mertz & Docherty, 2012; Peng et al., 2015). The technical requirements of the jump may influence the peak landing vGRF, as ballet-specific jumps tend to result in greater vGRF than traditional jumps (A. Mattiussi et al., 2021). Two of these studies, however, included sample sizes of one and two participants, which may not be generalisable to all dancers (Dworak et al., 2006; Gorwa et al., 2020). Loading rate has also been described during several ballet-specific jumps, with values ranging between 10–223 $BW \cdot s^{-1}$ (Arnwine & Powell, 2020; Dworak et al., 2006; Gorwa et al., 2020; Lee et al., 2012; Peng et al., 2015), however, similar to the vGRF data, two of these studies had very small sample sizes (Dworak et al., 2006; Gorwa et al., 2020).

Much of the existing literature investigating jumping and landing in ballet dancers may not apply to elite populations as it has largely been conducted on non-professional or non-ballet populations (A. Mattiussi et al., 2021). The aim of this study was to investigate the effect of foot position (parallel, first, second, fourth, and fifth) on ankle joint mechanics and vGRFs across jump landings in professional ballet dancers. We hypothesised that ballet-specific foot positions would have different biomechanics characteristics compared to parallel and one another.

METHODS

Study Design

A cross-sectional study design was employed to investigate the effect of foot position on ankle mechanics and vGRF (Supplementary Material 1) during jump landing in professional ballet dancers. Dancers attended one data collection session where they completed five countermovement jumps (CMJ) across seven different foot positions (Figure 1). All testing was conducted in the *BLINDED* during the 2020-21 season.

Participants

Twenty-seven professional ballet dancers (men: $n = 14$, age: 26.7 ± 4.9 y, height: 1.79 ± 0.04 m, mass: 72.6 ± 5.2 kg, professional: 8.9 ± 5.2 y; women: $n = 13$, age: 24.0 ± 3.7 y, height: 1.68 ± 0.04 m, mass: 55.2 ± 3.3 kg, professional: 5.9 ± 3.8 y) volunteered to participate in this study from a cohort of 105 dancers (25.7%). Dancer ranks included Apprentices ($n = 3$), Artists

(n = 8), First Artists (n = 6), Soloists (n = 2), First Soloists (n = 5), and Principals (n = 3). Participants were required to not have sustained a lower extremity time-loss injury in the six weeks prior to testing. Informed consent was obtained prior to data collection and ethical approval was provided by *BLINDED* Ethics Committee in accordance with the Declaration of Helsinki.

Procedure

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. Curved rigid moulded clusters with four retroreflective markers were attached to the lateral aspect of the right shank using cohesive elastic tape and electrical tape (Figure 2).

Participants completed five maximal bilateral CMJs across seven different foot positions: parallel, first, second, fourth with the front leg on the force platform (fourth front), fourth position with the back leg on the force platform (fourth back), fifth position with the front leg on the force platform (fifth front), and fifth position with the back leg on the force platform (fifth back; Figure 1). Dancers were informed to maintain ballet technique to the best of their ability (i.e., turned out across ballet positions and crossed in fourth and fifth positions). 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 a jump in each foot position was performed within a set. Twenty seconds of intra-set rest and two minutes of inter-set rest were provided (Pereira et al., 2008).

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 horizontal, and Y was the cross-product of Z and X.

Data Analysis

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 (de Leva, 1996). Individual and cluster markers for the foot and shank were used to track segments during dynamic trials. An inverse kinematics approach was used to estimate the pose of the segments (Lu & O'Connor, 1999), filtered at 8 Hz and 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 whilst the proximal segment was used as both the reference segment and the resolution coordinate system when determining ankle angular velocity. Kinematic data and segmental inertial data were combined with ground reaction force data to calculate joint kinetics using an inverse dynamics approach (de Leva, 1996). Marker and ground reaction force data were filtered at 8 Hz using a low-pass fourth-order Butterworth filter, determined via residual analysis (Winter, 2009). Ankle joint moment and joint power were normalised for comparisons between participants (Hof, 1996)—leg length was replaced with height (Atack et al., 2019) and an adjusted calculation for normalized power was used to provide a dimensionless value (Bezodis et al., 2010):

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

$$Normalised\ Ankle\ Power = \frac{P}{mg^{3/2}h^{1/2}}$$

Vertical ground reaction force data were reprocessed and filtered at 250 Hz using a low pass fourth-order Butterworth filter, determined via residual analysis (Winter, 2009), to calculate normalised vGRF:

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

The start of each landing phase was identified where vGRF was >50 N following the period of flight. The end of each landing phase was calculated as the point at which data collection ceased. Data were extracted from the landing phase and variables were computed. Peak values of ankle mechanics and vGRF measures were calculated as the greatest value throughout the landing phase. through all planes of motion. Ankle excursion was calculated by subtracting the minimum ankle angle from the peak ankle angle. Loading rate was calculated using the following equation:

$$Loading\ Rate = \frac{Normalised\ Peak\ Landing\ vGRF}{Time\ to\ Normalised\ Peak\ Landing\ vGRF}$$

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.

Statistical Analysis

A repeated measures MANOVA was conducted to investigate within-subject multivariate main effects of foot position on ankle mechanics and vGRF during jump landings in professional ballet dancers using the R package *stats* (R Core Team, 2022). Extreme outliers—where values above $Q3 + 3 \times IQR$ or below $Q1 - 3 \times IQR$—were removed ($n = 22$; 0.8%) using the R package *rstatix* (Kassambara, 2020). A post-hoc sensitivity analysis revealed that a sample size of 27 participants was sensitive to detect an effect size = 0.232 ($\beta = 0.80$, $\alpha = 0.05$, Pillai V = 0.4, correlation among repeated measures = 0.5, measurements = 7) using G*Power 3 (Faul et al., 2007). The assumption of multivariate normality was violated and thus ordered quantile transformations were applied to all dependent variables using the R package *bestNormalize*

(Peterson, 2017). A parametric approach was selected over a non-parametric approach as a MANOVA is robust to type 1 error and power decrements and outperforms non-parametric equivalents in the presence of non-normal data (Finch, 2005).

Linear discriminate analyses (LDA) were conducted to investigate significant main effects using the R package *MASS* (Venables & Ripley, 2002). The LDA provides regression equations in which the contributions of all kinetic and kinematic outcome variables can be used to classify the main effect grouping variable (i.e., foot position). One additional post-hoc LDA was conducted based on visual inspection of the results from the initial LDA, where a hypothesis on how model accuracy may be improved was acted on (Hollenbeck & Wright, 2017). All data processing and statistical analysis were conducted using R (version 4.2.1, R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

The repeated measures MANOVA revealed a significant within-subject main effect of foot position ($F_6 = 6.6$; $p < .001$; Pillai = 2.9). The mean, standard deviation, and 95% CI for all variables across foot positions are presented in Supplementary Material 2. The mean, standard deviation, and 95% CI for all variables across men and woment are presented in Supplementary Material 3.

One LDA was performed to investigate the main effect of foot position which included all variables across all seven foot positions. Six linear discriminants were identified to classify foot position (LD1: 49.3%; LD2: 36.3%; LD3: 10.4%; LD4: 1.4%; LD5: 1.4%; LD6: 0.7%). The LDA investigating the effects of foot position had a classification accuracy of 56.8% when tested for performance. Clear clusters were visually observed between the symmetrical ballet foot positions (first and second), positions assessing the back foot (fourth back and fifth back), and positions assessing the front foot (fourth front and fifth front) when plotted (Figure 3). Thus, a second LDA was conducted where these foot positions were grouped such that only four different foot positions were input into the model (i.e., parallel, first and second combined, fourth back and fifth back combined, and fourth front and fifth front combined). Three linear discriminants were identified to classify grouped foot positions (LD1: 51.4%; LD2: 43.0%; LD3: 5.5%). The LDA investigating the effects of grouped foot position had a classification accuracy of 91.4% (60% improvement) when tested for performance. The results of both models investigating the effect of foot position are presented in Figure 3. The regression equations representing the three linear discriminants for grouped foot positions can be found in Figure 4. The mean, standard deviation, and 95% CI for all variables across the grouped foot positions are presented in Table 1.

Due to the relatively small contribution of LD3 (5.5%), only LD1 (51.4%) and LD2 (43.0%) are discussed in detail. Linear discriminate one was able to classify jump landings in parallel from all ballet-specific foot positions (Figure 3). The regression equation for LD1 revealed that frontal plane ankle joint angles and excursions and transverse plane excursions have a considerable contribution to the classification of parallel from all other ballet-specific foot positions (Figure 4). Further, transverse plane ankle joint moments, frontal plane ankle joint power, and jump height were also identified as important variables contributing to this classification. Linear discriminate two was able to classify jump landings in the grouped front foot position from all other positions (Figure 3). The regression equation for LD2 revealed that transverse plane ankle joint power and frontal plane ankle joint angles have a considerable contribution to the classification of jump landings in the grouped front foot position from all other positions. (Figure 4).

Both fourth and fifth positions demonstrated a greater peak ankle abduction angle compared to all other foot positions, with the grouped front foot involving six times more abduction compared to first and second, and three times more abduction compared to the grouped back foot (Table 1). Frontal plane ankle excursions were greatest in the grouped back foot position, with values 15–20% larger than all other positions. Grouped first and second position exhibited transverse plane excursions 1.5 times that of parallel, and grouped front and grouped back foot positions exhibited transverse plane excursions twice that of parallel (Table 1). Transverse plane ankle joint moments in parallel were at least twice that of all ballet foot positions. Conversely, frontal plane ankle joint power was 1.3–2.3 times greater in all ballet foot positions when compared to parallel. The grouped back foot peak ankle power in the transverse plane exhibited more than double that of all other foot positions. Jump height was comparable across all foot positions other than parallel where participants jumped an additional 3–4 cm (Table 1). Loading rate was 15% higher in grouped first and second position and grouped back foot position compared to parallel and front foot position. Vertical ground reaction force was 6–8% greater in first and second and the grouped front foot position when compared to parallel and the grouped back foot position.

DISCUSSION AND IMPLICATION

This is the first study to investigate the effect of parallel, first, second, fourth, and fifth positions on ankle mechanics and vGRF during jump landings in professional ballet dancers. The results demonstrated that foot position influences ankle mechanics and vGRF during jump landings in professional ballet dancers. Further, the results indicate that ankle mechanics and vGRFs are comparable between first and second positions, the back foot in both fourth and fifth positions, and the front foot in both fourth and fifth positions. In particular, the peak ankle joint angle in the frontal plane was able to discriminate between parallel and both grouped front and back foot positions. Peak transverse plane ankle power and frontal plane ankle joint angle were both able to discriminate between the grouped front foot and all other foot positions. These results highlight the biomechanical variance across these fundamental foot positions which may impact decision-making around technical and physical goal setting in professional ballet in a performance and rehabilitation context.

The initial LDA and the post-hoc LDA revealed new insights into how foot positions might be categorised based on ankle mechanics and vGRF. A 60% improvement in model classification accuracy was observed following the grouping of foot positions (ungrouped: 57%; grouped: 91%); demonstrating the similarities between first and second positions, the back foot in fourth and fifth position, and the front foot in fourth and fifth position. To that end, grouping these foot positions when considering ankle mechanics and vGRF is warranted and may aid in simplifying decision-making in applied environments. The results of the present study indicate that three-dimensional ankle kinetics and kinematics play a critical role in discriminating between different foot positions, particularly through the frontal and transverse planes. It is perhaps unsurprising that frontal and transverse plane kinematics were able to discriminate the grouped front and back foot positions in fourth and fifth from other positions due to the offset and asymmetrical nature of these positions when compared to parallel, first, and second.

Presently there is limited literature investigating different foot positions, making comparison challenging. Imura and Iino (2017) investigated parallel and first during take-off and observed no differences in peak ankle dorsiflexion angle, ankle plantarflexion moment, or ankle plantarflexion work between parallel and first. Conversely, when Ravn et al., (2007) investigated parallel and first during take-off, they observed peak sagittal plane ankle joint moments and powers in first position at least twice that of parallel. Ravn et al., (2007), however, performed no statistical analysis and only three participants were included, potentially leading to inflated results (Konietschke et al., 2021). Both of the aforementioned studies also used different methods to calculate kinetic outcome variables, limiting any direct comparisons with our analysis. The results from the present study indicate that sagittal plane kinetics and kinematics are poor classifiers of foot position compared to frontal and transverse plane kinetics and kinematics.

The landing vGRF observed in the present study (~2 × bodyweight) is comparable to values reported during continuous *échappé sauté* (a countermovement jump alternating the landing between fifth position and second position; Peng et al., 2015) and *sissonne fermée* (a horizontal jump from one leg landing in fifth position; Lee et al., 2012), but roughly half to a third lower than more technical jumps such as *grand jeté* (a travelling leap from on limb to the other with a split during flight; Arnwine & Powell, 2020) or *double tour* (a countermovement jump from and to fifth position with a 720-degree rotation while in flight; Dworak et al., 2006; Gorwa et al., 2020). It should be noted, however, that only a single limb was investigated during bilateral jumps in the present study and the total vGRF experienced through both limbs will be greater. Several studies have reported joint kinetics during ballet jumps (Gorwa et al., 2020; Perry et al., 2019), however, differences in equations make comparisons challenging. Further research examining joint mechanics during repeated jumping, travelling jumps, and unilateral jumps in different foot positions may reveal insights into the biomechanical demands of ballet jumps.

Practical Applications

The differences observed in ankle mechanics and vGRF during jump landings in different foot positions in the present study provide a basis for grouping foot positions. Jump landings across all ballet foot positions require greater peak ankle angles and excursions when compared to parallel, particularly in fourth and fifth positions. Thus, restoring ankle mobility during rehabilitation could be critical prior to returning to these positions in performance settings. The notably higher transverse plane peak ankle power observed during jump landings in the grouped back foot positions indicates a high rate of energy transfer while landing in these positions. To that end, exercises that emphasise rotational force or high rates of rotational force around the ankle may be warranted in professional ballet dancers. Further, when planning return-to-dance pathways following injury, it is recommended that jump (or *pointe*) exercises in which dancers land in fourth or fifth position may be introduced later than exercises in parallel, first, and second.

Strengths, Limitations, and Future Directions

This research is one of few studies investigating jumping actions in both male ballet dancers and professional ballet dancers (A. Mattiussi et al., 2021), demographics which have previously been under-studied in the ballet literature. Considering male ballet dancers and professional ballet dancers will typically be exposed to greater jumping demands than female dancers and non-professionals, respectively, it is important to understand these demographics in more detail (Shaw et al., 2021). Bilateral asymmetries or limb dominance may have affected the results of this study, as only the right limb was measured during bilateral jumps. Previous work, however, has found no association between a dancer's perception of limb dominance and their kinetics during jumping (Mertz & Docherty, 2012). Future work may wish to conduct a broader analysis of landing biomechanics in dancers which includes the trunk and entire lower extremity.

CONCLUSION

This study investigated the effect of foot position on ankle mechanics and vGRF in professional ballet dancers. The results identified that foot position influences ankle mechanics and vGRF during jump landings. Frontal and transverse plane ankle mechanics had the largest impact when discriminating between different foot positions, with jump landings in fourth and fifth demonstrating greater ranges of motion, moments, and power when compared to other foot positions. Adaptations in multiplanar force and rates of force development are warranted in professional ballet dancers. Finally, following injury, full ankle range of motion should be restored prior to returning to fourth and fifth positions.

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TABLE 1

Table 1. Mean ± SD [95% CI] of ankle mechanics and vGRF across grouped foot positions.

	Parallel	1st/2nd	4th/5th Back	4th/5th Front
Normalised Moment^{X}	0.098 ± 0.010 [0.079, 0.117]	0.092 ± 0.012 [0.068, 0.115]	0.102 ± 0.016 [0.071, 0.133]	0.101 ± 0.018 [0.065, 0.136]
Normalised Moment^{Y}	0.017 ± 0.008 [0.002, 0.033]	0.006 ± 0.006 [0.000, 0.017]	0.004 ± 0.003 [0.000, 0.010]	0.005 ± 0.004 [0.000, 0.014]
Normalised Moment^{Z}	0.010 ± 0.005 [0.000, 0.019]	0.005 ± 0.003 [0.000, 0.012]	0.002 ± 0.002 [0.000, 0.005]	0.005 ± 0.003 [0.000, 0.010]
Normalised Power^{X}	1.24 ± 0.20 [0.85, 1.63]	1.24 ± 0.23 [0.78, 1.70]	1.22 ± 0.25 [0.72, 1.72]	1.33 ± 0.30 [0.74, 1.92]
Normalised Power^{Y}	0.10 ± 0.05 [0.01, 0.20]	0.14 ± 0.06 [0.02, 0.26]	0.13 ± 0.07 [0.00, 0.27]	0.23 ± 0.09 [0.06, 0.40]
Normalised Power^{Z}	0.08 ± 0.03 [0.01, 0.14]	0.09 ± 0.04 [0.02, 0.16]	0.22 ± 0.06 [0.10, 0.34]	0.06 ± 0.03 [0.01, 0.11]
Velocity^{X} (°·s^{-1})	907 ± 68 [774, 1040]	945 ± 80 [788, 1102]	933 ± 84 [768, 1098]	895 ± 88 [722, 1068]
Velocity^{Y} (°·s^{-1})	97 ± 48 [3, 191]	88 ± 36 [16, 159]	103 ± 40 [26, 181]	125 ± 48 [31, 218]
Velocity^{Z} (°·s^{-1})	135 ± 50 [37, 234]	186 ± 74 [41, 330]	147 ± 61 [28, 266]	190 ± 60 [72, 308]
Angle^{X} (°)	103 ± 4 [94, 111]	103 ± 4 [94, 111]	106 ± 5 [97, 115]	104 ± 4 [95, 112]
Angle^{Y} (°)	2 ± 3 [-4, 8]	-2 ± 4 [-9, 5]	-4 ± 4 [-13, 5]	-13 ± 4 [-22, -4]
Angle^{Z} (°)	-7 ± 5 [-18, 3]	-5 ± 5 [-15, 5]	-4 ± 8 [-19, 11]	7 ± 4 [-2, 15]
Excursion^{X} (°)	64 ± 7 [50, 77]	69 ± 5 [58, 79]	68 ± 7 [54, 81]	70 ± 6 [59, 81]
Excursion^{Y} (°)	20 ± 4 [13, 27]	21 ± 4 [13, 29]	24 ± 4 [15, 32]	20 ± 4 [12, 28]
Excursion^{Z} (°)	11 ± 4 [4, 19]	15 ± 5 [5, 26]	18 ± 5 [7, 28]	20 ± 7 [8, 33]
vGRF (BW)	1.94 ± 0.45 [1.07, 2.82]	2.05 ± 0.56 [0.95, 3.14]	1.90 ± 0.39 [1.14, 2.66]	2.04 ± 0.58 [0.90, 3.17]
TTP vGRF (s)	0.09 ± 0.02 [0.05, 0.13]	0.08 ± 0.02 [0.04, 0.12]	0.09 ± 0.02 [0.04, 0.13]	0.09 ± 0.02 [0.05, 0.12]
Loading rate (BW·s^{-1})	26.9 ± 13.3 [0.9, 53.0]	30.5 ± 15.1 [0.9, 60.1]	30.7 ± 19.0 [0.00, 67.9]	26.5 ± 11.7 [3.6, 49.5]
Jump height (cm)	42.2 ± 7.7 [27.0, 57.4]	39.5 ± 7.0 [25.9, 53.2]	39.5 ± 6.4 [27.0, 52.0]	38.6 ± 6.6 [25.6, 51.6]

Superscripts X, Y, and Z represent the sagittal, frontal, and transverse planes, respectively. Ninety degrees represent ankle plantar grade for Angle^{X}, with greater values denoting dorsiflexion; positive values represent ankle adduction and internal rotation for Angle^{Y} and Angle^{Z}, respectively.

vGRF, vertical ground reaction force; TTP, time to peak

FIGURE 1

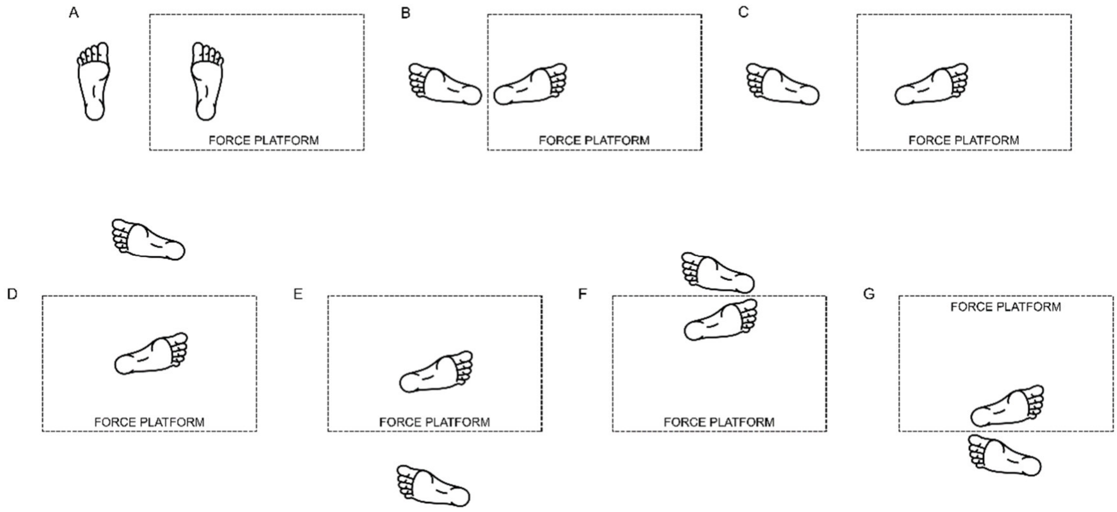

Figure 1. The foot positions tested in the present study with reference to the force platform. (A) parallel, (B) first, (C) second, (D) fourth back, (E) fourth front, (F) fifth back, (G) fifth front.

FIGURE 2

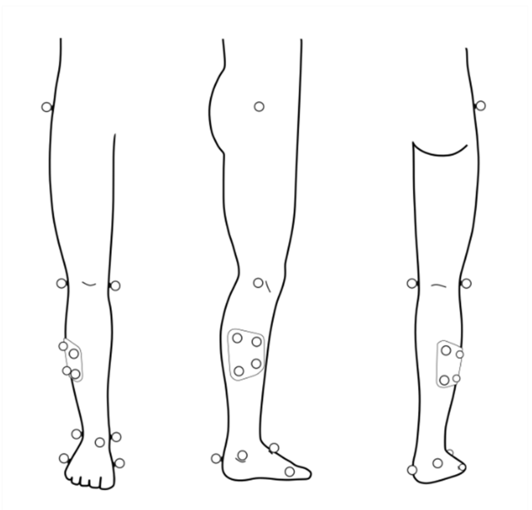

Figure 2. Marker placement on the right limb from the anterior, lateral, and posterior aspects.

FIGURE 3

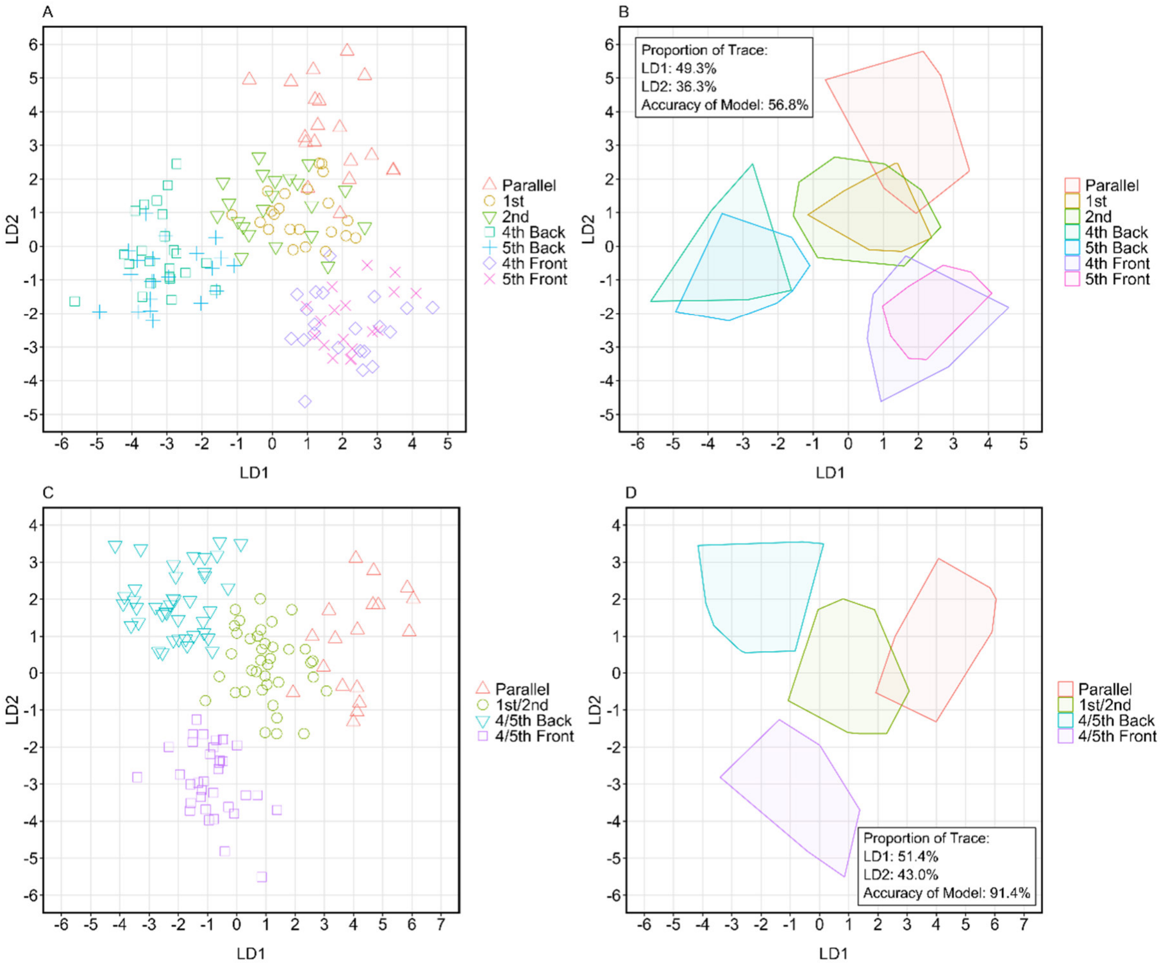

Figure 4. A) visualises the individual data and B) visualises the convex hull of the first linear discriminate analysis where seven individual foot positions were included. C) and D) show the results of the second linear discriminate analysis, where the seven foot positions were grouped following visual inspection.

LD, Linear discriminate.

FIGURE 4

	Angle^Y	Excursion^Z	Excursion^Y	Moment^Z	Power^Y	Jump height	Loading Rate	TTP vGRF	Moment^X	Angle^Z	Moment^Y	Excursion^X	Velocity^X	Power^X	Angle^X	Power^Z	Velocity^Z	Velocity^Y	vGRF
LD1 Relative Proportion	18%	11%	9%	9%	8%	7%	6%	4%	4%	4%	3%	3%	3%	3%	2%	2%	2%	2%	2%
LD1 Absolute Proportion	1.69	-1.01	-0.83	0.82	0.81	0.71	-0.58	-0.40	-0.38	0.37	0.29	0.27	-0.25	-0.24	-0.22	-0.18	0.18	-0.16	0.16

	Power^Z	Angle^Y	Angle^Z	Velocity^X	Power^X	vGRF	Moment^X	Angle^X	Power^Y	Velocity^Y	Excursion^Z	Jump height	Excursion^Y	Moment^Y	Excursion^X	Velocity^Z	Loading Rate	TTP vGRF	Moment^Z
LD2 Relative Proportion	17%	16%	6%	6%	5%	5%	5%	5%	5%	4%	4%	4%	4%	3%	2%	2%	2%	1%	1%
LD2 Absolute Proportion	1.06	0.98	-0.39	0.39	-0.34	0.09	0.33	0.33	-0.32	-0.28	0.27	0.27	-0.22	0.20	-0.15	-0.10	-0.10	0.09	-0.08

	Excursion^Z	Moment^X	vGRF	Excursion^X	Angle^Y	Loading Rate	Angle^X	Angle^Z	TTP vGRF	Moment^Y	Velocity^Z	Power^Z	Power^X	Moment^Z	Velocity^Y	Velocity^X	Power^Y	Jump height	Excursion^Y
LD3 Relative Proportion	9%	8%	8%	8%	8%	8%	7%	7%	7%	6%	4%	4%	4%	4%	3%	2%	1%	1%	0%
LD3 Absolute Proportion	-0.74	0.65	-0.65	-0.64	-0.61	0.61	0.59	0.59	0.54	0.51	-0.32	0.31	-0.29	0.28	0.21	-0.18	-0.08	-0.04	0.03

Figure 4. The canonical coefficients (referred to as absolute proportion) and relative percentage of each canonical coefficient to each linear discriminate (referred to as relative proportion) for the grouped foot positions following the second linear discriminate analysis. The absolute proportion can be used as a regression equation to calculate the linear discriminate value from individual dancer data. The relative proportion provides an understanding of how each variable contributes to the linear discriminate value. Superscripts X, Y, and Z represent the sagittal, frontal, and transverse planes, respectively.

LD, Linear discriminate; TTP, Time to peak; vGRF, vertical ground reaction force

SUPPLEMENTARY MATERIAL 1

The kinetic and kinematic outcome variables that were included in the present study are outlined in the table below. The X, Y, and Z planes represent the sagittal, frontal, and transverse planes, respectively.

Variable	Plane
Moment	X
	Y
	Z
Angle	X
	Y
	Z
Power	X
	Y
	Z
Velocity	X
	Y
	Z
Excursion	X
	Y
	Z
Vertical Ground Reaction Force	-
Time to Peak vGRF	-
Loading Rate	-
Jump Height	-

SUPPLEMENTARY MATERIAL 2

Mean ± SD [95% CI] of ankle mechanics and vGRF across all foot positions.

	Parallel	First	Second	Fourth Back	Fifth Back	Fourth Front	Fifth Front
Normalised Moment^X	0.098 ± 0.010 [0.094, 0.102]	0.093 ± 0.013 [0.088, 0.098]	0.090 ± 0.012 [0.086, 0.094]	0.099 ± 0.013 [0.094, 0.104]	0.105 ± 0.018 [0.099, 0.112]	0.102 ± 0.020 [0.094, 0.109]	0.099 ± 0.016 [0.093, 0.105]
Normalised Moment^Y	0.017 ± 0.008 [0.014, 0.020]	0.008 ± 0.006 [0.006, 0.010]	0.004 ± 0.005 [0.002, 0.005]	0.005 ± 0.003 [0.004, 0.006]	0.003 ± 0.003 [0.002, 0.004]	0.005 ± 0.004 [0.003, 0.006]	0.006 ± 0.005 [0.004, 0.008]
Normalised Moment^Z	0.010 ± 0.005 [0.008, 0.012]	0.005 ± 0.003 [0.004, 0.006]	0.004 ± 0.004 [0.003, 0.006]	0.001 ± 0.001 [0.001, 0.002]	0.002 ± 0.002 [0.001, 0.002]	0.005 ± 0.003 [0.004, 0.006]	0.005 ± 0.003 [0.004, 0.006]
Normalised Power^X	1.24 ± 0.20 [1.17, 1.32]	1.28 ± 0.23 [1.19, 1.36]	1.20 ± 0.24 [1.11, 1.29]	1.19 ± 0.24 [1.10, 1.28]	1.25 ± 0.27 [1.15, 1.35]	1.35 ± 0.34 [1.22, 1.48]	1.31 ± 0.26 [1.22, 1.41]
Normalised Power^Y	0.10 ± 0.05 [0.09, 0.12]	0.14 ± 0.06 [0.12, 0.17]	0.13 ± 0.06 [0.11, 0.15]	0.10 ± 0.05 [0.09, 0.12]	0.15 ± 0.09 [0.12, 0.19]	0.24 ± 0.09 [0.21, 0.28]	0.22 ± 0.08 [0.19, 0.25]
Normalised Power^Z	0.08 ± 0.03 [0.06, 0.09]	0.09 ± 0.03 [0.08, 0.10]	0.09 ± 0.04 [0.08, 0.11]	0.23 ± 0.06 [0.21, 0.26]	0.21 ± 0.06 [0.19, 0.24]	0.06 ± 0.03 [0.05, 0.07]	0.06 ± 0.02 [0.05, 0.07]
Velocity^X (°·s^{-1})	907 ± 68 [881, 933]	941 ± 72 [914, 968]	949 ± 89 [916, 983]	923 ± 77 [894, 952]	942 ± 92 [907, 976]	906 ± 91 [872, 941]	883 ± 86 [851, 916]
Velocity^Y (°·s^{-1})	97 ± 48 [79, 115]	88 ± 40 [73, 103]	88 ± 34 [75, 100]	110 ± 42 [94, 126]	97 ± 37 [83, 111]	131 ± 46 [114, 148]	118 ± 50 [100, 137]
Velocity^Z (°·s^{-1})	135 ± 50 [116, 154]	171 ± 72 [144, 198]	200 ± 74 [172, 228]	143 ± 54 [122, 163]	151 ± 67 [126, 176]	191 ± 62 [168, 215]	189 ± 60 [166, 211]
Angle^X (°)	103 ± 4 [101, 104]	104 ± 5 [102, 106]	102 ± 4 [100, 103]	106 ± 5 [104, 107]	107 ± 4 [105, 108]	103 ± 4 [101, 105]	104 ± 5 [102, 106]
Angle^Y (°)	2 ± 3 [1, 3]	-3 ± 3 [-4, -2]	-2 ± 4 [-3, 0]	-3 ± 4 [-5, -1]	-5 ± 4 [-7, -3]	-13 ± 5 [-15, -11]	-13 ± 4 [-15, -11]
Angle^Z (°)	-7 ± 5 [-9, -6]	-4 ± 5 [-6, -2]	-6 ± 4 [-8, -4]	-6 ± 9 [-9, -2]	-3 ± 5 [-5, -1]	7 ± 4 [6, 9]	6 ± 5 [5, 8]
Excursion^X (°)	64 ± 7 [61, 66]	68 ± 6 [66, 71]	69 ± 5 [67, 71]	67 ± 7 [65, 70]	68 ± 7 [65, 70]	70 ± 6 [68, 72]	70 ± 6 [68, 72]
Excursion^Y (°)	20 ± 4 [19, 21]	22 ± 4 [20, 23]	21 ± 4 [20, 23]	24 ± 4 [22, 25]	24 ± 5 [22, 25]	20 ± 5 [18, 22]	20 ± 4 [18, 21]
Excursion^Z (°)	11 ± 4 [10, 13]	16 ± 5 [14, 18]	15 ± 6 [13, 17]	17 ± 5 [15, 19]	18 ± 6 [16, 21]	21 ± 6 [18, 23]	20 ± 7 [18, 23]
vGRF (BW)	1.94 ± 0.45 [1.77, 2.11]	1.92 ± 0.47 [1.74, 2.10]	2.17 ± 0.61 [1.94, 2.40]	1.88 ± 0.36 [1.75, 2.02]	1.92 ± 0.42 [1.76, 2.07]	2.16 ± 0.60 [1.93, 2.39]	1.91 ± 0.54 [1.71, 2.12]
TTP vGRF (s)	0.09 ± 0.02 [0.08, 0.10]	0.08 ± 0.02 [0.07, 0.09]	0.09 ± 0.02 [0.08, 0.09]	0.08 ± 0.03 [0.07, 0.09]	0.09 ± 0.02 [0.08, 0.10]	0.09 ± 0.01 [0.08, 0.09]	0.09 ± 0.02 [0.08, 0.09]
Loading rate (BW·s^{-1})	26.9 ± 13.3 [21.9, 32.0]	29.6 ± 13.1 [24.6, 34.5]	31.3 ± 17.0 [24.9, 37.7]	33.6 ± 20.2 [25.9, 41.2]	28.0 ± 17.6 [21.4, 34.7]	27.2 ± 10.1 [23.4, 31.0]	25.8 ± 13.4 [20.8, 30.9]
Jump height (cm)	42.2 ± 7.7 [39.2, 45.1]	40.7 ± 7.1 [38.0, 43.4]	38.4 ± 6.7 [35.9, 40.9]	40.0 ± 6.5 [37.6, 42.5]	39.0 ± 6.3 [36.6, 41.3]	38.4 ± 6.6 [35.9, 40.8]	38.9 ± 6.8 [36.4, 41.5]

SUPPLEMENTARY MATERIAL 3

Mean ± SD [95% CI] of ankle mechanics and vGRF across women and men.

	Women	Men
Moment^X	0.092 ± 0.013 [0.085 ,0.099]	0.103 ± 0.016 [0.095 ,0.111]
Moment^Y	0.006 ± 0.006 [0.003 ,0.009]	0.007 ± 0.007 [0.003 ,0.011]
Moment^Z	0.004 ± 0.004 [0.002 ,0.006]	0.005 ± 0.004 [0.003 ,0.007]
Power^X	1.17 ± 0.22 [1.05 ,1.29]	1.34 ± 0.26 [1.21 ,1.48]
Power^Y	0.14 ± 0.07 [0.10 ,0.18]	0.17 ± 0.09 [0.12 ,0.22]
Power^Z	0.12 ± 0.08 [0.07 ,0.16]	0.12 ± 0.08 [0.08 ,0.16]
Velocity^X	922 ± 68 [885 ,960]	921 ± 97 [870 ,972]
Velocity^Y	105 ± 47 [79 ,130]	103 ± 42 [81 ,126]
Velocity^Z	178 ± 72 [138 ,217]	161 ± 60 [129 ,192]
Angle^X	105 ± 5 [102 ,107]	103 ± 4 [101 ,106]
Angle^Y	-5 ± 7 [-9 ,-1]	-5 ± 6 [-8 ,-2]
Angle^Z	-3 ± 7 [-7 ,1]	-1 ± 9 [-5 ,4]
Excursion^X	70 ± 5 [67 ,73]	66 ± 7 [62 ,70]
Excursion^Y	21 ± 5 [18 ,23]	22 ± 3 [20 ,24]
Excursion^Z	16 ± 6 [13 ,19]	18 ± 7 [14 ,21]
vGRF	1.88 ± 0.43 [1.65 ,2.12]	2.08 ± 0.55 [1.79 ,2.37]
TTP vGRF	0.09 ± 0.02 [0.08 ,0.10]	0.08 ± 0.02 [0.07 ,0.09]
Loading rate	25.9 ± 14.9 [17.8 ,34.0]	31.7 ± 15.1 [23.8 ,39.6]
Jump height	33.6 ± 3.3 [31.8 ,35.4]	45.3 ± 3.9 [43.2 ,47.3]

DISCLOSURES

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PATIENT INVOLVEMENT There was no patient or public involvement in the design, conduct or reporting of this study.

DATA SHARING No data are available.