

Applications of Biomechanical Foot Models to Evaluate Dance Movements Using Three-Dimensional Motion Capture: A Review of the Literature

Kimberly P. Veirs,¹ Andrew H. Fagg,² Amgad M. Haleem,³ Lynn M. Jeffries,⁴ Ken Randall,⁵ Susan B. Sisson,⁴ and Carol P. Dionne⁴

Abstract

Dance movement requires excessive, repetitive range of motion (ROM) at the foot-ankle complex, possibly contributing to the high rate of injury among dancers. However, we know little about foot biomechanics during dance movements. Researchers are using three-dimensional (3D) motion capture systems to study the in vivo kinematics of joint segments more frequently in dance-medicine research, warranting a literature review and quality assessment evaluation. The purpose of this literature review was to identify and evaluate studies that used 3D motion capture to analyze in vivo biomechanics of the foot and ankle for a cohort of dancers during dance-specific movement. Three databases (PubMed, Ovid MEDLINE, CINAHL) were accessed along with hand searches of dance-specific journals to identify relevant articles through March 2020. Using specific selection criteria, 25 studies were identified. Fifteen studies used single-segment biomechanical foot models originally created to study gait, four used a novel two-segment model, and six utilized a multi-segment foot model. Nine of the studies referenced common and frequently published gait marker sets and four used a dance-specific biomechanical model with purposefully designed foot segments to analyze the dancers' foot and ankle. Description of the biomechanical models varied, reducing the reproducibility of the models and protocols. Investigators concluded that there is little evidence that the extreme total, segmental, and inter-segmental foot and ankle ROM exerted by dancers are being evaluated during dance-specific movements using 3D motion capture. Findings suggest that 3D motion capture is a robust measurement tool that has the capability to assist researchers in evaluating the in vivo, inter-segmental motion of the foot and ankle to potentially discover many of the remaining significant factors predisposing dancers to injury. The literature review synthesis is presented with recommendations for consideration when evaluating results from studies that utilized a 3D biomechanical foot model to evaluate dance-specific movement.

Key Points

- Review findings procured little evidence that the extreme total, segmental, and inter-segmental foot and ankle range of motion exerted by dancers are being evaluated during dance-specific movements using three-dimensional (3D) motion capture.
- Most researchers using 3D motion capture systems to study the in vivo kinematics of the foot and ankle during dance movements utilize single-segment foot models, which evaluate the foot and ankle as a single segment, rigid body.
- The present findings support the use of multi-segment foot models to evaluate the total, segmental, and intersegmental motion of the foot and ankle joints to evaluate dance-specific movements.

Introduction

Traditional dance styles, such as classical ballet, contemporary dance, jazz, tap, ballroom Latin dance, and Irish dancing, require dancers to possess excessive joint ranges of motion (ROM) for proper technique execution and desired aesthetics.¹⁻⁸ Although these dance styles have different technical demands and style-specific movements, all styles require excessive ankle and foot ROM that may put the dancer at increased risk for injury. For example, dancers frequently transition into demi-pointe relevé (standing on the balls of the feet with toes extended) from plié ("to bend"; full dorsiflexion of the ankles with the knees flexed). During this transition,

1. Oklahoma City University, Oklahoma City, Oklahoma, USA.
2. University of Oklahoma, Norman, Oklahoma, USA.
3. University of Oklahoma Health Sciences Center, Oklahoma City, Oklahoma, USA, and Cairo University College of Medicine, Cairo, Egypt.
4. University of Oklahoma Health Sciences Center, Oklahoma City, Oklahoma, USA.
5. University of Oklahoma Health Sciences Center, Tulsa, Oklahoma, USA.

Correspondence:
Kimberly P. Veirs
kpveirs@okcu.edu

Funding Statement: The authors have no disclosures. The authors report no conflicts of interest in regard to the information presented in this work.

the dancer moves from end-range dorsiflexion (DF) into end-range plantar flexion (PF) of the ankle.⁶ Additionally, balancing in the demi-pointe relevé position transmits up to four times the dancer's body weight through the foot.⁹ Classical ballet dancers have to withstand much greater stresses and strains when transitioning into the en pointe position (standing on the toes in pointe shoes with maximum plantar flexion of the ankle joint and toes in neutral position, relative to the long axis of the foot^{9,10}).

Extreme, repetitive ROM demands placed on the foot and ankle joints is thought to be a contributing factor to the unchanging injury rates among dancers.^{4,11} Recent studies assessing cohorts of dancers from several different traditional styles of dance report high rates of lower extremity (LE) injuries.¹²⁻¹⁶ Yau et al.¹³ conducted a retrospective analysis of electronic medical records (EMRs) over a 6-year period of 480 ballet and contemporary high school and collegiate dancers at a premiere arts academy in the United States and found that, of the 1,014 dance-related injuries, 443 (43.7%) involved the foot or ankle. Cahalan et al.¹⁶ surveyed 37 elite adolescent Irish dancers who reported a total of 63 injuries over a 1-year duration, of which 27 (42.8%) involved the foot and ankle. Several studies reported annual injury rates as high as 85% and 95% in pre-professional and professional ballet dancers, respectively.^{12,14,15} These aforementioned examples of injury rates across different dance styles are a major concern for dance medicine clinicians and researchers, as they have not changed since first studied in the 1960's.^{17,18} Furthermore, the specific risk factors related to these unchanging rates are largely unknown.¹⁹⁻²²

Several factors possibly related to dance injury risk include variables intrinsic to the dancer (e.g., ROM demands,^{6,23} strength, endurance, and motor control¹²) and variables extrinsically affecting the dancer (e.g., composition of dance floors²⁴⁻²⁷ and construction and stiffness of different types of dance shoes^{11,28-32}). Numerous authors have described the kinetic (e.g., joint moments) and kinematic (e.g., joint ROM) factors of various lower extremity joints (hip, knee, ankle, and foot) during dance movement.^{4,9,11,25,27,30,33-51} Several studies examined the extreme ankle DF ROM in plié positions and PF ROM in demi-pointe and en pointe relevé.^{1,4,6,9,23,37-39,48} However, two primary discrepancies arise in the literature: 1. the amount of ROM that is required in the midfoot and forefoot (e.g., first metatarsophalangeal [MTP] joint) in these positions,^{35,48,52,53} and 2. by what means should the joint angles of the foot and ankle be measured when assessing functional ROM of the dancer.^{1,4,6} Moreover, there is no evidence in the literature concerning how these elements may relate to each other as contributing factors to injury in dancers, for example, how biomechanical factors of the trunk and lower extremities are affected when ROM is limited at the first MTP joint, midfoot, or ankle.

Five functional joints or segments compose the foot-ankle complex: the ankle (talocrural), the subtalar, the midtarsal or transverse tarsal, the tarsometatarsal (TMT) or Lisfranc joint, and the MTP joints. These joints move about oblique axes relative to the three planes of the body (sagittal, frontal, and transverse). The foot complex is composed of the subtalar, midtarsal, TMT, and MTP joints that constitute three distinct

segments: the hindfoot, midfoot, and forefoot. The foot complex allows tri-planar movement (movement in all three body planes simultaneously) with three degrees of freedom (3DOF) in two directions allowing for a total of 6DOF: supination (plantar flexion, adduction, and inversion) and pronation (dorsiflexion, abduction, and eversion). Tri-planar movement is an example of how joints of the foot-ankle complex also move relative to adjacent joints (inter-segmental movement). The purest tri-planar motion occurs at the subtalar joint as its joint orientation allows for equidistant movement in all three planes.^{23,54}

The total ROM required to attain the extreme PF ROM during dance movement is proposed to come from a summation of movement from all of these aforementioned joints in the foot-ankle complex.^{23,55,56} Therefore, evaluating functional foot and ankle ROM of dancers requires a measure of 1. total ROM, 2. inter-segmental ROM, and 3. individual foot and ankle joint ROM in the foot-ankle complex.^{1,4,6,57} Three-dimensional (3D) motion capture systems to study the kinematics of joint segments of joint segments are being used more frequently in research laboratories and clinics for analyzing gait because of the system's ability to measure the foot and ankle in all three planes of movement (sagittal, frontal, and transverse).⁵⁸ More recently, dance medicine researchers are utilizing the 3D systems for analyzing dance-specific postures and movements.³⁴

Three-Dimensional (3D) Motion Capture

Typical motion capture laboratories have cameras mounted in a fixed configuration connected to dedicated computers to track reflective surface markers on the body of the moving person during protocol-specific activity. A digitizing procedure captures the 3D coordinates of each marker that is subsequently used as the basis for calculating segmental or derived joint angles.⁵⁸ The advanced motion capture system determines biomechanical torques produced at anatomical joints and other landmarks targeted to analyze kinetics and other properties of generated movements (kinematics) during each task performed in the calibrated 3D space.⁵⁹ The biomechanical model is defined by the number and location of all the model reference frames or segments created by application of the reflective markers on meaningful anatomical landmarks.⁶⁰

Biomechanical models vary in the degree of specificity to which they measure motion, especially at the foot and ankle. Standard gait analysis models consider the foot as a single, rigid segment or vector often referred to as the "rigid body assumption."^{61,62} Single-segment models neglect to consider the dynamic interactions of the three distinct segments of the foot complex.^{60,61,63} As a result, they fail to capture all of the kinetic and kinematic contributions of the foot complex⁵⁸ and induce greater risk of measurement error because the inter-segmental bone movements in the foot are not considered.⁶³ Three-dimensional multi-segment foot models (3DMFMs) incorporate three or more distinct segments of the foot to measure how they move relative to one another and aim to reduce the likelihood of measurement error as a result of the rigid body assumption.⁶³ Nonetheless, investigators must consider not only the strengths but also the limitations of 3D motion capture systems when

designing a research protocol, such as unavoidable systematic errors.

Skin movement, or soft tissue artifact (STA), is the unavoidable systematic and random error in measured marker trajectories between skin-mounted markers and underlying bone⁶⁴ occurring whenever skin-mounted markers are used.⁶⁵ Several studies have tested criterion-related validity of 3D motion capture using reflective surface markers on the skin by comparing it to the “gold standard” of measurement using intracortical bone pins.^{58,66,67} Maiwald et al.⁶⁷ reported no within-subject differences between intracortical bone pins and surface markers using 95% confidence intervals for kinematics of the foot during gait. Nester et al.⁶⁸ compared three different methods of tracking: skin-mounted markers, markers attached to tracking plates, and intracortical bone pins during gait. They reported few statistically significant differences between any of the three methods for the 18 parameters tested ($> 3^\circ$ tracking difference for 35% of the parameters and $> 5^\circ$ tracking difference for 3.5% of the parameters).

Intracortical bone pins are drilled into bone under anesthesia to secure motion capture marker arrays on top of the skin to represent the intrinsic articulations of bones in the foot during in vivo movement analysis.⁶⁷ Due to the invasive nature of this procedure, surface markers and tracking clusters are commonly used in motion capture gait laboratories and clinics and authors commonly discuss the inherent errors of STA when interpreting results.⁶⁸ The aforementioned validity studies provide evidence that when reflective surface markers are attached to the skin using a systematic procedure, the data yielded from 3D motion capture represents actual bone and joint movement. Three-dimensional motion capture systems have been validated as robust measurement tools capable of reliably and accurately collecting whole body biomechanical data.⁶⁹

New knowledge gained from using 3D motion capture and robust biomechanical foot models to study dance movement include: 1. elucidating relationships of joint kinematic patterns, such as rising onto demi pointe relevé and en pointe in the female ballet dancer; 2. developing normative ROM data specific to dancers; 3. demonstrating common trends between two groups of dancers stratified by specific foot joints with limitation; and 4. leading to a better understanding of associations of risk factors for injury not yet understood, that will ultimately improve the overall evaluation and clinical care of dancers. Dance medicine researchers are starting to incorporate 3D motion capture to evaluate dance-related movement, therefore, a review of the literature and related quality assessment of studies is warranted. The purpose of this literature review is to identify and evaluate studies that utilized 3D motion capture systems to analyze the in vivo biomechanics of the foot and ankle during dance-specific movement.

Methods

Search Strategy

Database searches encompassed all published studies through March 2020 of PubMed, Ovid MEDLINE, and CINAHL using keywords: dance, dancer(s), foot models, motion capture, biomechanics, kinetics, and kinematics. Hand searches for relevant articles were performed for the *Journal of Dance Medicine & Science*, *Medical Problems of Performing Artists*, and *Dance Medicine and Science Bibliography (seventh edition)*. Inaccessible articles, including conference proceedings and outdated resources no longer in publication, and clinical commentaries were excluded from review. The initial literature search eliminated articles based on title or duplication and those not available in full text or English, including studies translated into English from another language (Fig. 1). Studies not available in full text,

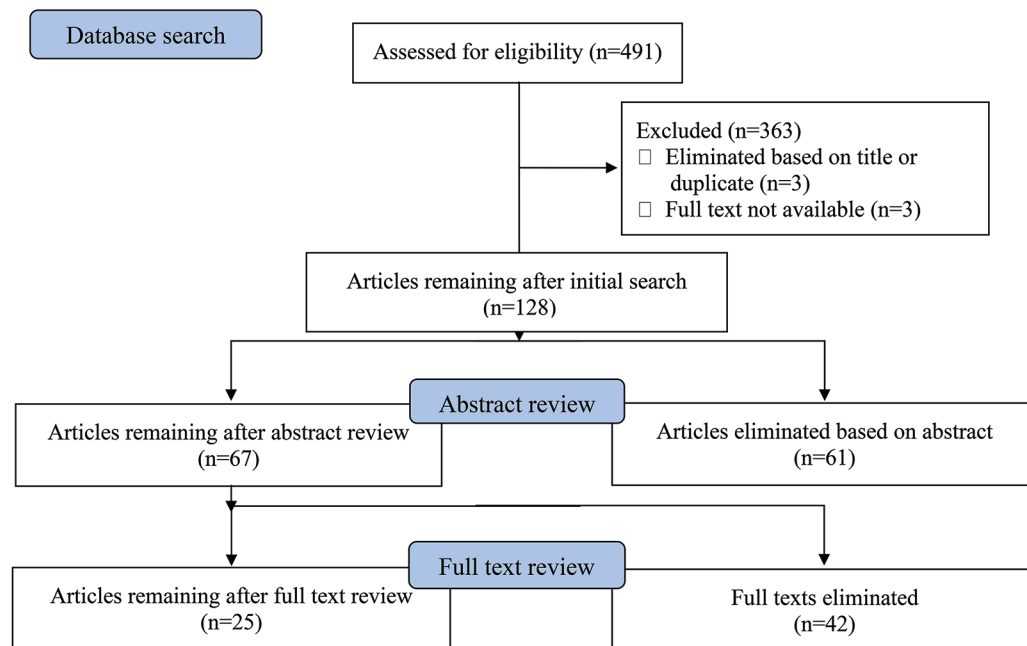


Figure 1 Methodology used for the literature search of articles using biomechanical foot models and three-dimensional motion capture to evaluate dance movements.

Table 1 Data Collection Instrument^{58,71,72}

	Yes	No
1. Is the hypothesis, aim, and objective of the study clearly described?		
2. Are the main outcomes to be measured clearly described in the Introduction or Methods section? Purpose/specific aim(s)		
3. Are the characteristics of the participants included in the study clearly described? Age: Gender: Dance level: Type of dance: Number of participants:		
4. Are the variables of interest clearly described and operationally defined? Independent variables: Dependent variables:		
5. Is 3D motion capture the primary measurement tool used? System: Number of markers: Number of cameras: Measurement frequency: Additional device(s) used:		
6. Was the biomechanical model used sufficiently described? If yes, number of segments: Modeled foot segments: Barefoot or shoe used during data collection, type of shoe:		
7. Are the distributions of principal confounder, interaction, or effect modification variables described? If yes, what are they?		
8. Are the main findings of the study clearly described?		
9. Does the study provide estimates of the random variability in the data for the main outcomes? Non-normally distributed data: IQR Normally distributed data: SE, SD, or CI		
10. Have actual probability values been reported (eg 0.035 rather than < 0.05) for the main outcomes except where the probability value is less than 0.001? Level of significance used:		
	Yes	No
11. Were the statistical tests used to assess the main outcomes appropriate? (e.g., non-parametric tests used for small sample sizes)		
External validity (generalizability)		
12. Were the participants in the study representative of the entire population from which they were recruited?		
13. Can the results be generalized to other dancers, settings, or times?		
Internal validity		
14. Did the authors report how or if they attempted to reduce or prevent testing effects that have the potential to change the outcome of the dependent variable measures (e.g., when the dancer warms up or practices trial specific movements; was the protocol the same for all participants)? Describe:		
15. Was there adequate adjustment for confounding in the analyses from which the main findings were drawn? If analysis did not include testing for confounding variables, answer "unable to determine".		
Validity of the measurement tool		
16. Was validity of the measurement tool(s) described?		

(Continued on next page)

Table 1 Continued

	Yes	No	Unknown
Reliability			
17. Was reliability measured?			
Test-retest reliability (ICC)			
Rater reliability:			
Interrater (ICC)			
Intra-rater (ICC)			
Internal consistency (Chronbach's alpha)			
Other (eg MDD, MCID)			
Power (probability that a test will lead to rejection of H_0 . Percent of the time we would correctly demonstrate a statistical difference and reject H_0 if actual differences exist.)			
18. Was a power analysis conducted a priori to determine sample size?			
If no, was this a pilot study?			
19. Was Effect Size reported?			
20. Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than the level of significance?			

such as conference proceedings, were excluded because details related to methodology and description of the biomechanical model and marker sets typically are not included. The criteria for retaining or discarding the remaining articles for abstract review were based on specific inclusion and exclusion criteria.

Inclusion and Exclusion Criteria

Articles included were studies that met the following inclusion criteria: 1. classified as either descriptive, exploratory or experimental research designs; 2. utilized a 3D motion capture system as the primary measurement tool; 3. used a biomechanical model that included a description of the ankle and foot segments; 4. described a protocol incorporating dance-specific movements; and 5. investigated a cohort of dancers. Articles were excluded with topics that concerned aerobic fitness and free or social dance movement styles, because these styles are not considered theatrical forms of dance.⁷⁰ Examples of theatrical dance forms include classical ballet, contemporary dance or modern, jazz, tap, hip hop, ballroom, and Irish dancing.

Full Text Review Procedure and Quality Assessment

The first author completed an inclusion criteria checklist for all articles remaining for full text review. Articles meeting all five inclusion criteria were kept for final analysis. A worksheet, created specifically for this literature review, served as the data collection instrument (Table 1). The worksheet was specific for non-randomized studies and aimed to ensure the literature review was a systematic evaluation of biomechanical models that include foot segments⁵⁸ and study methodology.^{71,72} The worksheet included a checklist to ensure all inclusion criteria were met and quality was assessed for the following components: hypothesis, aim, or objectives; description of the participants; variables of interest and operational definitions; main outcomes; and description of the study design, the type of 3D motion capture system, the biomechanical model, and foot segments.

Criteria specifically used to assess the methodological quality of each study included determination of appropriate use of statistical tests. Each of the following components related to psychometric properties were notated: the distribution of principal confounders, interaction of effect modification variables, estimates of random variability for the main outcomes, specific probability values to determine statistical significance, external validity (generalizability), internal validity, validity of the measurement tool, reliability, and power.^{71,72}

Results

Review Selection and Identification

Figure 1 shows the literature review procedure. The initial data base search generated 491 articles. One-hundred and twenty-eight abstracts were reviewed, of which 67 articles remained for full-text review. Forty-two articles were eliminated after full-text review because they did not meet one or more inclusion criteria. Nineteen articles were eliminated because the foot model (e.g., number of foot segments or marker placement on the foot and ankle) was not defined or a reference for the foot model used in the biomechanical model was not provided, making it impossible to analyze the fidelity of their results. Fifteen studies were excluded because the foot or ankle were not included in the research question. Four protocols did not use 3D motion capture systems and four others did not use dance-specific movements. Twenty-five studies met all five inclusion criteria and were selected for this review.

Description of Studies

Number of foot segments (one-, two-, or multi-segment [three or more segments]) was the primary factor used to group the information extracted from the articles (Tables 2 through 7) a priori. This decision was based on previous literature that described how incorporation of two or more foot segments in a biomechanical model better describes the contribution of the

Table 2 Single-Segment Foot Models (N = 15), Study Design, Purpose, Specific Aims, Foot and Ankle Variables Measured, and Results

Study	Study Design	Purpose and Specific Aim	Independent (I) and Dependent (D) Variables	Results
Abraham et al. ⁷³	Descriptive, cross-sectional (N = 23)	1. To report and compare dance-specific, functional ankle kinematic, kinetic, and self-reported level of difficulty (balance, muscular force, and concentration) properties of repeated and static elev� among adolescent female dance students 2. To investigate the relationships between elev� performance properties and participants' demographics (age, height, weight, dancing experience, and leg dominance) 3. To describe the relationships between kinematic properties in both elev� tasks	I: Two conditions of elev� task (feet parallel): repeated elev� and static elev� hold (balancing) D: Ankle kinematics: PF maximum angle and total PF ROM (deg) and kinetics: inter-leg WBD (percentage of body weight)	Repeated elev�: high internal consistency (Chronbach's alpha > 0.99); ICC: 0.98, 95% CI: 0.97 to 0.99. Ankle PF ROM significantly greater for repeated than static elev� but linearly related
Chang et al. ⁸¹	Exploratory, cross-sectional (N = 29)	1. To investigate the effect of skill on kinematic and coordination variables in the "Alternate Basic" in Cha-Cha-Cha. 2. To determine the nature and direction of changes with skill in kinematic DOF and coordination from a whole-body perspective.	I: Dancer skill level (beginner, intermediate, expert) D: Kinematics: joint angles (3 DOF: flex/ext [ankle DF/PF], add/abd, IRot/ERot; deg) plane amplitudes (max angle – min angle; deg), angular joint speed (deg/sec), intra-limb joint coupling; variance (%)	Joint amplitudes: inc sig for most body segments but at the ankle, only right ankle add/abd. Joint speed: inc sig with skill level for all segments, except left ankle. Dec joint LE joint coupling with inc skill level; inc variance with inc skill level.
de Mello Veiro et al. ⁷⁵	Exploratory, cross-sectional (N = 17)	To evaluate the midfoot longitudinal arch height and correlate it with active hip external rotation (ER) in dancers during static postures and technical steps of classical ballet	I: Dance-specific positions/movements: first position, demi-pli�, battement fondu � la second�, pas jet� � la second�, and grand jet� � la second� D: Foot kinematics: midfoot longitudinal arch height (mm)	Arch height significantly reduced during battement fondu � la second�, pas jet� � la second�, and grand jet� � la second�
Gontijo et al. ⁷⁴	Descriptive, cross-sectional (N = 20)	1. To establish a methodology to quantify, using kinematic evaluation, the technical criteria that guide the correct execution of all phases of the pli� (simultaneous hip, knee, and ankle flexion) 2. To explore whether experienced ballet dancers respect those criteria when performing the pli�	I: Pli� movement (4 types): demi-pli� in first position, grand pli� in first position, demi-pli� in second position, and grand pli� in second position D: Foot kinematics: midfoot longitudinal arch height (cm) and knee and ipsilateral foot alignment/distance using the midpoint of the foot markers (cm)	Great stability of the midfoot in all 8 phases of the pli� described as uniform body weight distribution between the hallux, fifth toe, and heel
Hopper et al. ²⁵	Single-factor repeat measures, cross-sectional (N = 14)	To examine the ankle joint mechanics of dancers performing drop landings on dance floors with varied levels of force reduction	I: Level of dance floor force reduction: 4 types of flooring D: Ankle joint kinematics: DF ROM (deg), peak angular velocity and acceleration (N kg ⁻¹) and ankle kinetics: PF peak joint moments (N kg ⁻¹) and power (W)	All ankle kinetics and kinematics sig increased (increased load across the ankle) when force reduction of the floor decreased

(Continued on next page)

Table 2 Continued

Study	Study Design	Purpose and Specific Aim	Independent (I) and Dependent (D) Variables	Results
Imura et al. ⁴¹	Descriptive, cross-sectional (N = 12)	To investigate the effect of hip external rotation (turnout) on lower limb kinetics during vertical jumps by classical ballet dancers	I: Hip position during jump: external rotation and neutral position D: Ankle joint kinematics: DF and PF ROM (degrees) and angular velocity (deg s ⁻¹) and kinetics: joint torque (Nm) and power (W)	No sig diff for kinematics or kinetics at the ankle between hip positions
Kadel et al. ⁷⁶	Descriptive, cross-sectional (N = 4)	To describe kinematic, kinetic, and electromyography analyses of ballet dancers performing four common dance movements on pointe	I: Four dance movements: rise to demi-pointe position, élevé, pique passé (onto one foot), a two-foot spring up to pointe D: Ankle kinematics: PF and DF ROM (deg) and kinetics: joint moment (N kg ⁻¹)	Greatest PF ROM following élevé; when en pointe, regardless of movement: DF ankle moment occurs
Lin CF et al. ³⁹	Descriptive, cross-sectional (N = 13)	1. To investigate and establish the contribution of the ankle joint during the relevé en pointe movement from a biomechanical point of view 2. To investigate symmetry between dominant and non-dominant sides	I: 1. Three phases of the relevé: starting position, transient phase, relevé en pointe position 2. Dominant/non-dominant sides D: Ankle kinematics: average maximum PF ROM (deg), peak angular velocity (deg s ⁻¹) and kinetics: peak joint moment en pointe (N kg ⁻¹)	Movement patterns highly coordinated between sides (ICC = 0.99); moderate correlation in ankle joint moment patterns (ICC = 0.66)
Lin CW et al. ⁷⁸	Descriptive, cross-sectional (N = 26)	To investigate physiological differences exhibited by experienced and novice dancers, respectively, when performing pirouette with dominant and non-dominant leg supports, respectively. (n = 13 per group)	I: Dancers' experience level: experienced and novice D: Ankle kinematics: maximum PF angle; LE kinetics: peak GRF, peak resultant GRF	No sig diff in ankle PF angle between groups; Sig diff peak force in ant-post direction
Lin CW et al. ⁴⁰	Descriptive, cross-sectional (N = 26)	To investigate the different postural control strategies exhibited by experienced and novice dancers in ballet turns (pirouettes) (n = 13 per group) (*Secondary data analysis: Lin CW et al., 2013)	I: 1. Dancers' experience level: experienced and novice; 2. Support leg: dominant and non-dominant side D: Ankle kinematics: maximum PF angle	Sig diff in PF angles during turns between sides for both groups
Lin CW et al. ⁷⁷	Descriptive, cross-sectional (N = 33)	To investigate how ankle sprains effect postural and muscular control during grand plié in ballet dancers (n _{injured} = 13; n _{uninjured} = 20)	I: 1. Ankle injury condition: injured (ankle sprain) and not injured; 2. Dominant and non-dominant side D: Ankle kinematics: maximum and total ROM of DF and eversion (deg)	Injured group: sig greater max ankle DF angle and smaller max ever angle on dominant side

Table 2 Continued

Study	Study Design	Purpose and Specific Aim	Independent (I) and Dependent (D) Variables	Results
Pappas et al. ²⁶	Single-factor repeat measures, cross-sectional (N = 44)	1. To determine the effect on dancers of an inclined surface (raked stage) on joint angles and joint moments during a single leg-landing task from a 30 cm platform 2. To examine the effect of sex and the interaction of sex and floor condition on kinematic and kinetic lower extremity variables during a landing task. (n _{males} = 14; n _{females} = 27)	I: 1. Floor inclination condition: 5 different levels of slope; 2. Sex: male or female D: Ankle and foot kinematics: ankle DF and foot abduction angle (deg); ankle and foot kinetics: ankle DF and foot abduction and eversion peak joint moment (N kg ⁻¹)	Inclined surface: sig effect on joint angles at peak vertical GRF and peak moments; females: sig decreased peak ankle DF moment than males
Picon et al. ⁸⁰	Descriptive, cross-sectional (N = 28)	1. To determine how aspects of dynamic turnout differ during sauté in first position in female classical ballet dancers with different training backgrounds and levels of experience in ballet 2. To determine what hip, knee, and ankle ROMs, and their variability, contribute dynamically to turnout during sauté in first position in the different groups evaluated	I: 3 groups: 1. Experienced from Royal Academy of Dance (RAD) (n = 13); 2. Experience from mixed teaching methods (n = 7); 3. Inexperienced from RAD (n = 8) D: Ankle kinematics: transverse plane ROM (Mean ± SD), angular ROM, and coefficient of variability (CV) and mean qualitative pattern of the angular variation of the ankle during the entire sauté time series analyzed (ankle ER [deg])	No sig diff between groups for transverse plane ROM (ER) at the ankle. Diff in movement pattern consistency verified visually (movement graphs) and quantitatively (CV)
Rocha et al. ⁷⁹	Descriptive, cross-sectional (N = 3)	1. Quantify the typical range of motion at the feet, knees, and hips in experienced and highly skilled tap dancers 2. Determine the time taken to perform different tap dance steps and movement phases 3. Examine symmetry in amplitude and timing between the right and left legs	I: Three tap dance steps: nerve beats, brush brush stamps, heel ball walks D: Ankle kinematics: total ROM (deg) and time to complete movement based on movement in space of specific joint markers (seconds)	Min of 10° Ankle ROM required for each step (range: 10° to 66.8°). Avg. time to perform each step varied (range: 0.50 sec to 4.03 sec)
Wild et al. ⁷	Descriptive, cross-sectional (N = 14)	To investigate the effects of fatigue on the peak lower limb and trunk angles as well as the peak lower limb joint forces and moments of competitive female Irish dancers during the performance of a dance-specific single-limb landing	I: Fatigue condition: pre-fatigue and post-fatigue D: Ankle kinematics: peak joint angles (deg) and kinetics: peak joint moment (N kg ⁻¹)	Post-fatigue: sig dec ankle PF and greater ant shear and compressive ankle forces

Table 3 Two-Segment Foot Models (N = 4), Study Design, Purpose, Specific Aims, Foot and Ankle Variables Measured, and Results

Study	Study Design	Purpose and Specific Aim	Independent (I) and Dependent (D) Variables	Results
Jarvis and Kulig ⁴⁸	Single-factor repeat measures, cross-sectional (N = 10)	To compare joint motion and net joint moments at the metatarsophalangeal joints during three different dance movements ranging in demands at the foot and ankle joints	I: Dance movement: relevé, sauté, and saut de chat leaps D: MTP joint kinematics: peak joint extension (deg) and kinetics: peak flexor net joint moment (N kg ⁻¹) in the sagittal plane	Sig greater peak ext during relevé than the two jumps; Sig greater net joint moment during saut de chat leaps
Jarvis and Kulig ⁴⁹	Descriptive, cross-sectional (N = 30)	To compare biomechanical demands placed on the lower extremity joints during the takeoff and landing phases of saut de chat leaps	I: Two phases of the saut de chat leap: takeoff and landing D: Ankle and MTP kinematics: joint angles (deg) and kinetics: peak net joint moment (N kg ⁻¹) in the sagittal plane	Sig greater joint moment at ankle and MPT during takeoff and at the hip during landing
Lee et al. ⁸²	Descriptive, cross-sectional (N = 22)	To find the neuromuscular and biomechanical characteristics in dancers with and without ankle injury during a jump-landing Sissonne Fermée task. (n _{injured} = 11; n _{uninjured} = 11)	I: Ankle injury condition: injured or not injured D: Ankle and foot kinematics: peak joint angles (deg)	Injured group: Sig greater peak ankle eversion angle, sig smaller hindfoot-to-tibial ever angle
Lin CF et al. ³⁷	Descriptive, test-retest (N = 20)	To examine the effect of fatigue on the balance, movement pattern, and muscle activities of the lower extremities in ballet dancers during relevé on demi-pointe	I: Fatigue condition: pre-fatigue and post-fatigue D: Ankle kinematics: joint angles (deg) in the sagittal, frontal, and transverse planes	Sig diff in ankle angle in all three planes during relevé

foot during movement⁵⁸ and decreases risk of measurement error than a single-segment model that assumes the foot and ankle as a rigid body.⁶³ Fifteen of the 25 studies utilized single-segment foot models,^{7,25,26,39-41,73-81} four studies applied a two-segment foot model,^{37,48,49,82} and six studies incorporated a multi-segment foot model.^{5,11,28,29,35,83} Three studies did not report the specific number of foot segments and only reported one set of data for the foot and ankle. Therefore, they were included in the single-segment foot model group.^{74,75,79}

Study Design

Twenty-four of the 25 articles reviewed were cross-sectional studies (all data were collected at one point in time⁷²) but with different study designs and purposes (Tables 2, 3, and 4). Fifteen of these 24 studies were descriptive designs that primarily aimed to investigate, compare or describe variables of interest observed in static postures or during dance-specific movements.^{7,37,39-41,48,73,74,76-80,82,83} Six of the studies were single-factor, repeated measure designs that evaluated one variable at different levels (e.g., types of footwear, inclination or slope of the floor, or dance movements).^{11,25,26,28,29,48} Three studies were exploratory designs that aimed to determine relationships between variables⁷² assessed during dance-specific movements.^{5,75,81} Two aforementioned studies were actually secondary data analyses^{29,40} from previous work.^{11,78} Since the secondary analysis studies measured different kinematic

and kinetic variables of the foot and ankle and were different from the originally published article, they were included in the literature review. Carter et al.³⁵ was the only test-retest, methodological design study of the 25 studies that tested reliability of a proposed foot model specifically to evaluate dance movement in two sessions over two consecutive days (Table 4).

Study Participants

All of the studies included a convenience sample of a cohort of healthy, uninjured dancers recruited from local dance schools, professional companies, or universities in the area local to the respective biomechanics' laboratory. All of the studies reviewed clearly described the participant demographics (e.g., age, sex, dance level), inclusion and exclusion criteria used for participant recruitment, and number of participants (Tables 2, 3, and 4). One study compared the kinematics of typical jump landings between dancers to non-dancers.³ Two studies included dancers with ankle injury to compare their movement patterns with healthy, uninjured dancers.^{77,82} Twenty-one of the 25 studies explicitly stated which genre or style their participants practiced: 12 evaluated ballet dancers,^{35,37,39,41,74-78,80,82,84} three evaluated jazz dancers,^{11,28,29} three evaluated both ballet and contemporary dancers,^{2,48,49} and tap dancers,⁷⁹ Latin ballroom,⁸¹ and Irish dancers⁷ were evaluated in one study each (Tables 5, 6, and 7). The other four studies did not specify the style of dance their participants practiced.^{25,26,73,83} Because

Table 4 Multi-Segment Foot Models (N = 6) , Study Design, Purpose, Specific Aims, Foot and Ankle Variables Measured, and Results

Study	Study Design	Purpose and Specific Aim	Independent (I) and Dependent (D) Variables	Results
Azevedo et al. ⁸³	Descriptive, cross-sectional (N = 30)	To investigate and compare the multi-segmented foot kinematics between professional dancers and non-dancers during forward and lateral single-leg jump-landings	I: Group: professional dancer (PD) and non-dancer (ND) D: Sagittal and frontal hindfoot-tibia and forefoot-hindfoot angles and sagittal hallux-forefoot kinematics angles at 3 different positions of the landing: initial contact, peak vertical ground reaction force, and peak knee flexion	Initial contact: PD's greater hindfoot-tibia and forefoot-hindfoot sagittal plane PF angles in both directions Peak vertical ground reaction force and peak knee flexion: PD's greater hindfoot-tibia DF angles in the sagittal plane Sagittal hindfoot-tibia and forefoot-hindfoot excursions greater PD than ND
Carter et al. ³⁵	Methodological study; test-retest (N = 6)	To determine the intra- and inter-assessor repeatability of a modified Rizzoli Foot Model for analyzing the foot kinematics of ballet dancers	I: Dance-specific positions/movements: parallel stance, turnout pli��, turnout stance, turnout rise and flex-point-flex D: Foot and ankle kinematics to determine intra- and inter-assessor reliability (ICC) of the proposed foot model	Poor to excellent ($0.5 > ICC \geq 0.75$) intra- and inter-assessor repeatability for all kinematic variables
Carter et al. ⁵	Exploratory, cross-sectional (N = 18)	To use a dance-specific multi-segment foot model to determine the lower leg and foot contributions to turnout that female university-level ballets use to accentuate their turnout	I: Natural double leg up-right posture and 3 first position conditions: functional turnout, forced turnout and saut��s in first position. D: Kinematic adjustments; hindfoot ever, midfoot and forefoot abd, navicular drop (i.e., lowering of the medial longitudinal arch) and first MTP joint abd	Hindfoot ever and midfoot abd: sig inc in functional turnout compared to double leg up-right posture. Hindfoot ever: accounts for variability of foot abd; a positive predictor of foot abd in all first position conditions. Navicular drop: sig inc during saut�� compared to functional and forced turnout
Fong Yan et al. ²⁸	Single-factor repeat measures, cross-sectional (N = 16)	To quantify the externally observed angle of plantar flexion in various jazz shoes compared with barefoot and to compare the sagittal plane bending stiffness of the various jazz shoes	I: Foot condition (shoe stiffness): Barefoot and 3 different jazz shoes D: Ankle, midfoot, and MTP kinematics: maximum joint PF (deg)	Compared to BF: all shoes sig restricted midfoot PF, one shoe restricted ankle PF, no sig diff at MTP.
Fong Yan et al. ¹¹	Single-factor repeat measures, cross-sectional (N = 16)	To describe the 3D kinematics of saut�� landings and takeoffs in second position and to evaluate the effect of various jazz shoe designs on the 3D kinematics in these movements	I: Foot condition (footwear): barefoot and 4 different jazz shoes D: Impact attenuation on the heel and forefoot; gross joint stiffness at ankle and midfoot	For all shoes: dec ROM of ankle in frontal plane and midfoot in all 3 planes; restricted midfoot and MTP motion compared to BF
*Fong Yan et al. ²⁹	Single-factor repeat measures, cross-sectional (N = 16)	1. To quantify the impact attenuation characteristics of different designs of jazz shoes using a mechanical testing rig 2. To investigate the effect of different jazz shoe designs on dancers' joint stiffness during a dance jump landing (*Secondary data analysis from Fong Yan et al., 2014)	I: Foot condition (shoe stiffness): barefoot and 4 different jazz shoes D: Ankle, midfoot, and MTP PF (deg)	Impact attenuation: sig diff for all jazz shoe designs; stiffness: sig diff BF and 3 shoe types

*Secondary data analysis study; Abd: abduction, Add: adduction, Ant: anterior; Dec: Decreased; Deg: Degrees; DF: dorsiflexion; Deg/sec: degrees per second; diff: difference; Ever: eversion; Ext: extension; Flex: flexion; IRot: internal rotation; ERot: external rotation, MTP: metatarsophalangeal joint; PF: plantar flexion; ROM: range of motion; sig: significant.

Table 5 Single Segment Foot Models (N = 15), Measurement Tools and Movements Evaluated

Study	Dance Style	Movements Evaluated	Marker Set-Up	Measurement Tools
Abraham et al. ⁷³	Not specified	Elevé in sixth position (parallel)	BF	2 digital cameras for 3D motion capture; 2 independent force plates
Chang et al. ⁸¹	Latin Ballroom	Alternate Basic in Cha-Cha-Cha	Not specified (figures in pictorials are BF)	Cortex 3, 14-camera motion capture system
de Mello Veiro et al. ⁷⁵	Ballet	1. First position 2. Demi-plié 3. Battement fondu la seconde 4. Pas jeté a la seconde 5. Grand jeté a la seconde	BF (Vicon plug-in marker set-up and right navicular marked)	Vicon motion capture system
Gontijo et al. ⁷⁴	Ballet	Demi-plié and grand plié in first and second positions	BF*	Four JVC video cameras and a 3D Peak Performance calibrator
Hopper et al. ²⁵	Dancers from “performing arts” school	Drop landings on dance floors with various levels of force reduction	BF*	Vicon, 12-camera motion system; one AMTI force plate
Imura et al. ⁴¹	Ballet	Jumps with 1. Hips externally rotated/turned out (TJ) 2. Hips parallel or neutral (NJ)	Soft ballet shoes; all of the same brand*	Vicon, 8-camera motion capture system; 2 force plates
Kadel et al. ⁷⁶	Ballet	1. Rise to demi-pointe position, 2. Elevé (rise to the en pointe position) 3. Pique passé (onto one foot) 4. Two-foot spring up to pointe	Pointe shoes* (Vicon plug-in marker set-up)	Vicon motion capture system
Lin CF et al. ³⁹	Ballet	Relevé en pointe	Pointe shoes*	HIRES motion capture system; two force plates
Lin CW et al. ⁷⁸	Ballet	Pirouettes (turns) en dehor (to right: clockwise turns; to left: counter-clockwise turns)	Soft ballet shoes*	Eagle, 8-camera motion capture system
Lin CW et al. ⁴⁰	Ballet	Pirouettes (turns) en dehor (to right: clockwise turns; to left: counter-clockwise turns)	Soft ballet shoes*	Eagle, 8-camera motion capture system; two force plates
Lin CW et al. ⁷⁷	Ballet	Grand plié in first position	Not specified* (ballet slippers pictured)	Eagle, 8-camera motion capture system; one force plate; surface EMG
Pappas et al. ²⁶	Not specified (professional company dancers)	Single leg landing onto different inclined surfaces; male and female differences	Tennis shoes* (with no heel)	Eagle, 8-camera motion capture system; AMTI multicomponent force plate
Picon et al. ⁸⁰	Ballet	Sauté in first position	BF	Optitrack FLEX: V100, 6 infrared cameras; one AMTI force plate
Rocha et al. ⁷⁹	Tap	Tap dance steps: 1. Nerve beats 2. Brush brush stamps 3. Heel ball walks	Tap shoes*	Vicon, 10-camera motion capture system
Wild et al. ⁷	Irish dance	Irish-dance leap	Soft Irish-dance shoes*	Vicon, 18-camera motion capture system; multi-channel force plate

BF: Barefoot; *Marker set-up not described.

Table 6 Two-Segment Foot Models (N = 4), Measurement Tools and Movements Evaluated

Study	Dance Style	Movements Evaluated	Marker Set-Up	Measurement Tools
Jarvis and Kulig ⁴⁸	Ballet & contemporary	1. Relevé 2. Sauté 3. Sauté de chat leaps	BF	Qualisys, 11-camera motion capture system; AMTI force plates
Jarvis and Kulig ⁴⁹	Ballet & contemporary	Sauté de chat leaps	BF	Qualisys, 11-camera motion capture system; AMTI force plates
Lee et al. ⁸²	Ballet	Sissonne Fermee jump-landing task	Pointe shoes*	Eagle motion capture system; 1 force plate; 10-channel surface EMG
Lin CF et al. ³⁷	Ballet	Relevé in demi-pointe	Soft ballet shoes*	Eagle, 8-camera motion capture system; surface EMG

BF: Barefoot; *Marker set-up not described.

Table 7 Multi-Segment Foot Models (N = 6), Measurement Tools and Movements Evaluated

Study	Dance Style	Movements Evaluated	Marker Set-Up	Measurement Tools
Azevedo et al. ⁸³	Not specified	Forward and lateral jump landings	BF	
Carter et al. ³⁵	Ballet	1. Parallel stance 2. Turnout plié and stance 3. Turnout rise 4. Flex-point-flex	BF (investigators practiced marker set-up on bony landmarks)	Vicon, 12-camera motion capture system
Carter et al. ⁵	Ballet, modern	1. Functional turnout 2. Forced turnout 3. Sautés in slightly open first position	BF	Vicon, 12-camera motion capture system
Fong Yan et al. ²⁸	Jazz	Point-flex-point	BF (control condition) and 3 different jazz shoes (bony landmarks palpated through the shoe for marker placement on outside of shoe)	Eagle and Cortex, 14-camera motion capture system; custom-built mechanical shoe dynamometer
Fong Yan et al. ¹¹	Jazz	Sautés in second position	BF (control condition) and 4 different jazz shoes (bony landmarks palpated through the shoe for marker placement on outside of shoe)	Eagle and Cortex, 14-camera motion capture system
Fong Yan et al. ²⁹	Jazz	Sautés in second position	BF (control condition) and 3 different jazz shoes (bony landmarks palpated through the shoe for marker placement on outside of shoe)	14-camera motion analysis system; force platforms; custom-built mechanical shoe dynamometer

these four aforementioned studies did not explicitly state the genre of dance practiced by their participants, results are not generalizable to a specific dance style whereas the results from the 21 studies that clearly reported genre could be compared.

Data Collection Tools and Protocols

All studies described the 3D motion capture system used to collect data, including number of cameras in the motion capture space and measurement frequency. Most studies reported the technical components required for data collection

in a 3D space, such as calibrating the reflective markers in the standard, static position prior to data collection and describing tracking marker placement and joint centers (e.g., hip, knee, and ankle). Some studies paired the motion capture system with other measurement tools, such as force plates to calculate ground reaction forces (GRF) and center of pressure (COP) and electromyography (EMG) to record muscle activity (Tables 5, 6, and 7). All of the studies described a standardized protocol including: dance-specific static positions tested and dynamic movement trials; instructions given to each participant; de-

scription of the temporal aspects of the trials (e.g., performed at dancers own pace or to a specific tempo set by a metronome or music); whether data was collected on both legs or one leg (e.g., the “dominant” leg); the time allotted for warm up; and how the participants learned and practiced the protocol-specific movements. Additionally, all studies included a description of the protocol-specific dance movements with operational definitions or photographs allowing even readers who do not know dance-specific pedagogy to understand what was examined.

Variables of Interest

The primary purpose of the studies reviewed were analyses of specific kinetic and kinematic variables during dance-specific movements (Tables 5, 6, and 7) stratified by one or more independent variables (Tables 2, 3, and 4). Seven of the 25 studies evaluated more than one movement,^{5,35,48,74-76,79} while four others assessed two variations of one type of movement (e.g., vertical jumps in two directions).^{3,40,41,78} The other 14 study protocols evaluated only one movement, including relevé (rising into demi-pointe or en pointe from plié),^{37,39} élevé (rising into demi-pointe or en pointe with straight legs),⁷³ plié,⁷⁷ jump take-off and landing (e.g., sauté, saut de chat leaps, Sissonne Fermée),^{7,11,25,26,29,49,80,82} point-flex-point (open kinetic chain PF-DF-PF of the foot and ankle),²⁸ and the Alternate Basic in the Cha-Cha-Cha.⁸¹

The independent variables for 20 of the 25 studies involved factors related to the level of the dancer, such as expert or novice, injury status, or the dance-specific movement or position under investigation. The independent variables for the other five studies evaluated the effects of an extrinsic factor on the kinematics or kinetics of the dancers’ foot (Tables 5, 6, and 7). Three of these studies evaluated the stiffness of different jazz shoes on the dancers’ ability to plantar flex the foot.^{11,28,29} The other two studies examined the effects of different floors with regards to incline or slope²⁶ and force reduction²⁵ on the dancers’ foot when landing from jumps. “Foot condition” describes if the data was collected barefoot (BF) or shod (wearing a shoe). Ten protocols were performed entirely barefoot, 13 with style-specific shoes (e.g., jazz, ballet, pointe, tap, or soft Irish-dance shoes), one with tennis shoes, and one did not specify foot condition.

Regardless of study design, number of foot segments, and independent variables, kinetic and kinematic dependent variables measured with 3D motion capture were generally similar (Tables 2, 3, and 4). The primary dependent variables for most of the studies were ankle and foot kinematics in the sagittal plane: ankle PF/DF angles (deg [maximum, total, amplitude]), angular velocity (deg s⁻¹), acceleration (N kg⁻¹), and MTP joint extension angles (deg). The most frequently measured kinetic dependent variables included ankle PF/DF peak and net joint moments (N kg⁻¹), power (W), torque (Nm), and MTP peak flexor net joint moment (N kg⁻¹). Six of the 25 studies measured movement in the transverse and frontal planes.^{5,26,77,80,81,83} Three studies measured medial longitudinal height by evaluating navicular drop during various static positions (e.g. demi- and grand- plié)^{5,74,75} and dynamic movements (e.g., landing from jumps).^{5,75,83} Thus, the variables measured in the studies

reviewed collectively demonstrate the wide-ranging use for 3D motion capture to examine in vivo static and dynamic, dance-specific movements under a variety of foot and external conditions.

Biomechanical Models

Fifteen of the studies reviewed used a single-segment biomechanical foot model originally created to study gait, four created a novel two-segment model, and six utilized a multi-segment foot model. Nine studies referenced a common and frequently published gait marker set, such as the Helen Hayes,^{37,40,77,78,82} the Vicon™ plug-in,^{75,76} the Cleveland Clinic,⁸⁰ and the Oxford Foot Model.⁸³ Only four studies used a dance-specific biomechanical model with purposefully designed foot segments to analyze the dancers’ foot and ankle.^{5,35,48,49} Description of the biomechanical models varied, as such, reproducibility of the models and protocols by other investigators also varied.

Explicitly stating where markers are placed on the body is important for precisely describing what is being measured with 3D motion capture,⁸⁵ particularly when a novel or modified marker-set is applied. For example, two groups of authors cited previous papers that described the biomechanical model and marker set placement they used to allow the reader to reference the secondary source.^{7,25} Wild et al.⁷ referenced the University of Western Australia static lower limb marker set and stated they used a modification of the marker set placement.⁸⁶ Hopper et al.²⁵ reported parameters from a previous study analyzing gait: high repeatability for all sagittal plane kinematics ($r^2 > 0.85$) and high within- and between-tester reliability for DF and PF ROM (ICC > 0.85). Although Wild et al.⁷ referenced the original article pertaining to their model for the reader to reference and Hopper et al.²⁵ cited psychometrics pertaining to kinematics of the ankle from a previous study, it was unclear as to how marker sets created to analyze gait kinematics reliably measure dynamic dance-specific movements. Only three groups of authors, amassing seven of the studies reviewed, Carter et al.,^{5,35} Fong Yan et al.,^{11,28,29} and Jarvis and Kulig,^{48,49} clearly explained the tracking marker set-up for their novel or modified biomechanical model. This finding from the literature review substantiates that it is not standard practice to test biomechanical gait models and marker set placement psychometrics prior to using them to analyze dance movement.

Some 3D motion capture studies are conducted without shoes to specifically test a biomechanical model. This eliminates the need to describe marker placement on or around the shoe. Few traditional dance styles, such as contemporary or modern, warrant barefoot data collection as it is typically performed unshod. Thirteen of the studies used style-specific shoes (e.g., jazz, ballet, pointe, tap, soft Irish-dance shoes) or tennis shoes, yet only one group reported where and how they placed reflective markers on the shoes. Fong Yan et al.^{11,28,29} palpated the bony landmarks through the jazz shoes for marker placement on the outside of the shoe. In contrast, Lin et al.³⁹ who examined movement of dancers wearing pointe shoes, only described where the landmarks would be placed on the barefoot not where or how they put the markers on the shoe. None of the others studies described how the markers should

be secured to the shoes for a more accurate marker tracking of the bony segments of the foot and ankle.

Dance-Specific Foot Models

Two groups of authors included in this literature review used a dance-specific biomechanical model with specified foot segments to analyze inter-segmental movement of the foot.^{5,35,48,49} Jarvis and Kulig⁴⁸ created a two-segment foot model to evaluate the specific sagittal plane kinematics and kinetics of the MTP joint separate from the other segments of the foot combined. The investigators reported differences in MTP joint kinetics (peak net joint moments [N kg^{-1}]) and kinematics (extension ranges of motion [deg]) between relevé and two different dance-specific jumping movements ($p < 0.001$) on 10 dancers. Jarvis and Kulig⁴⁹ conducted a second study using the same two-segment model to evaluate ankle and MTP kinematics (joint angles [deg]) and kinetics (peak net joint moment [N kg^{-1}]) in the sagittal plane during the takeoff and landing phases of sautés (split jumps). They reported that greater kinetic demands were placed on the MTP and ankle joints during the takeoff phase of the jump than the more proximal hip and knee joints tested ($p < 0.001$) on 30 unshod dancers.

Carter et al.³⁵ modified the Rizzoli Foot Model (RFM), a well-established 3DMFM, to determine its reliability for analyzing dynamic ballet movements. The investigators explicitly described six modifications and provided rationale for the changes made to create their proposed five-segment modified RFM. The aims of the modifications were to create a reliable marker set-up that would: 1. not impede joint movement and 2. minimize error due to STA.³⁵ Testing the foot model's intra-rater and inter-rater reliability (ICC) consisted of two investigators repeating the reflective marker placement protocol and participants repeating the dance-specific movement trials twice for two consecutive days. Carter et al.⁵ applied their modified RFM in a second study to evaluate kinematic adjustments and specific foot segment angles (degrees), including hindfoot eversion, midfoot and forefoot abduction, navicular drop, and first MTP joint abduction, during natural up-right standing and functional turnout (the dancers self-selected "preferred" turnout), forced turnout, and the landing phase of sauté jumps in first position ($n = 18$). Carter et al.⁵ determined that dancers' feet pronate in both turnout positions using hindfoot eversion and midfoot abduction. They reported that navicular drop was 11 mm greater during the landing phase of the sauté jump when compared to natural up-right standing posture ($p < 0.001$). Both of these dance-specific foot models analyzed the foot separate from the ankle and found significant differences in how the foot segments move during dance movement. This illustrates the significance of developing dance-specific foot models to analyze the dancers' foot separate from the ankle during dynamic movements and positions that are uniquely different from more linear movement, such as gait.

Quality Assessment of Methodology

One study did not perform any statistical analysis.⁷⁶ The other 24 studies used descriptive statistics, such as measures of central tendency (means and standard deviations or median,

minimum and maximum values) and reported probability values with a significance level of 0.01 or 0.05. Six studies reported testing for normality of the data and conducted the appropriate statistical analyses (parametric tests and non-parametric tests for normally and non-normally distributed data, respectively).^{5,72,74,75,80,81,83} For example, Gontijo et al.⁷⁴ reported non-normally distributed data and reported median, minimum, and maximum measures of central tendencies. Many the other studies used parametric testing even when the statistical conditions did not meet the requirements for using parametric statistics and violated the assumption of normally distributed data, such as small sample sizes (Tables 2, 3, and 4), not testing for normality, and using non-randomized samples.⁷² Considering all of the studies in the literature review were convenience samples, the possibility that sampling bias occurred could not be eliminated. Therefore, results should only be generalized to the populations from which each sample was recruited.⁷²

Dynamic activities, such as the movements described in the review studies, involve multiple factors intrinsic to the participant (e.g., age, experience in dance) and extrinsic in the environment (e.g., flooring, shoes). Subsequently, factors other than those of interest could be confounding or interacting with the results. Five studies described variables that could be potential confounding, interacting, or effect modifying variables.^{11,73,77,82,83} Two of these five studies, Abraham et al.⁷³ and Lee et al.,⁸² tested participants' demographics, age, height, and weight as possible confounding factors. Lin et al.⁷⁷ did not list specific interacting variables but reported that appropriate statistics were used when main effects or interactions were detected for between- and within-subject comparisons. Azevedo et al.⁸³ stated that no significant interactions were realized.

Fong Yan et al.¹¹ described shoe type as an effect modifier where the association between the predictor of interest (exposure: barefoot vs. shoe) and the outcome (kinematics of the foot and LE) were modified depending on the shoe condition. Because they tested for effect modification, they were able to conclude that placing markers on jazz shoes could overestimate skeletal motion. This information is relevant to researchers who wish to test dancers with style-specific shoes by providing evidence that the axes of motion of the foot joints may be different when comparing barefoot and shod conditions. The studies by Lin et al.⁷⁷ and Fong Yan et al.¹¹ both demonstrate that results could be misleading when variables of interest are affected by other factors and if not tested, could result in vastly different conclusions. Finally, these five studies illustrate the importance of testing for confounding, interacting, and effect modifying factors and interpreting results of studies that do not test for such factors with caution.

All 25 studies reviewed clearly described the main findings but the degree of methodological quality varied. None of the studies in the literature review reported validity of the 3D motion capture system used for data collection (e.g., QualisysTM, ViconTM, or EagleTM systems). Carter et al.^{5,35} specifically tested for reliability of their proposed 3DMFM specific for dance movement using intraclass correlation coefficients (ICC). Investigators reported high intra- and inter-rater reliability for

first MTP sagittal plane joint movement (ICC ≥ 0.75) and poor (ICC < 0.5) to excellent (ICC ≥ 0.75) inter-assessor reliability for three of the five inter-segmental angles during the point-flex-point trials, including the midfoot segments.³⁵ Carter et al.⁵ also reported high intra- and inter-rater reliability for first MTP joint transverse plane angles (ICC: 0.88). These ICC values span the full spectrum of reliability,⁷² which is why the authors reported a broad range of inter-rater reliability across all variables tested.³⁵ Summation of these findings provide evidence that using a multi-segment foot model has the potential to be a valuable tool to evaluate total, segmental, and inter-segmental ROM of the foot and ankle during dance-specific movement,³⁵ provided investigators test reliability to ensure consistency of results that are reproducible and free from error.⁷²

Gait studies specifically designed to test the repeatability of 3DMFM's report that clearly defining landmark locations for marker placement and practicing the protocol for marker set placement is essential for demonstrating repeatability of the model and reliability of the measures.^{87,88} Additionally, standardization of marker placement was found to reduce variability of measurement outcomes during gait by 20%.⁸⁹ Deschamps et al.⁹⁰ compared mean inter-session variability between a senior clinician and a novice clinician using the Leardini foot model marker set-up. Only 9% (9/100) of the mean ROM measures compared were significantly different between the two clinicians ($p < 0.05$). Carter et al.³⁵ were the only investigators that discussed how their protocol for marker placement could have affected the results. They concluded that the greater variation of inter-rater reliability compared to intra-rater reliability could be due to inconsistencies in marker placement, as neither of the two investigators practiced 3D foot marker placement prior to this study. Lee et al.⁸² and Azevedo et al.⁸³ reported that the same investigator placed the reflective markers on each participant to improve accuracy and repeatability of measurements. Implementing a standardized protocol for marker set placement is essential for reducing measurement error and increase reliability of the measures,⁸⁹ as was postulated by Carter et al.³⁵ Only four studies reported that their study had sufficient power to detect a clinically important effect,^{3,5,28,80} where the probability of a difference being due to chance is less than the level of significance.⁷¹

Discussion

Several 3D foot models configured specifically to study gait are identified in the literature and range in specificity from single to multi-segment foot models.^{58,60,61,63,85,91-95} Three-dimensional multi-segment foot models created for studying gait are frequently utilized for studying movements other than walking, such as running⁹⁶⁻⁹⁸ and dance. Bishop et al.⁹⁹ conducted a systematic review to critically evaluate how data obtained through 3DMFM was being reported. They concluded that inconsistencies for reporting methodological designs when creating or modifying a foot and ankle model demonstrates that there are no clearly defined standards in place. Synthesis of information collected from this dance-specific literature review echoes the findings of Bishop et al.⁹⁹ Methodological inconsistencies reported include how the authors describe the

biomechanical model and marker placement protocol, test for potential confounding or other extraneous variables, and measure the independent variables. The methodological differences between studies result in limited reproducibility by other investigators who wish to advance and build upon the current body of knowledge of dance movement biomechanics of the foot and ankle using 3D motion capture. Several consistencies were also reported between many of the 25 studies reviewed, including a description of study protocols, dependent variables and dance movements tested, and the cohort of dancers included.

Adapting or modifying a gait model specifically designed to analyze a linear movement, such as walking and running, should not be assumed to accurately reflect how the bony segments articulate during dynamic movements out of the sagittal plane (e.g., turning out, kicking, or jumping) and into extreme ranges of motion. Reliability and repeatability studies are necessary when creating or modifying an existing biomechanical foot model for use with dance-specific movement. Carter et al.^{5,35} were the only authors among those reviewed who tested the reliability of their modified gait model on a cohort of dancers. The dance-specific and multi-segment foot models used in the studies reviewed were found to be of moderate to high methodological quality, nonetheless, the psychometric parameters (e.g., validity and reliability) of the biomechanical foot models must be tested to ensure they are suitable for use when evaluating dance movement.^{58,62,69,72}

Fong Yan et al.¹¹ were the only investigators who compared the axes of motion of the foot joints during barefoot and shod conditions. Results from these comparisons indicate that skeletal motion may be overestimated when taking measurements. A marker set should be explicitly described and when shoes are worn during data collection, the markers on the outside of shoes must correspond to bony landmarks specified by the model and tested for reliability and accuracy. Future studies using style-specific dance shoes should include determination of minimally detectable differences (MDD) of measures.^{89,100} Bishop et al.¹⁰⁰ defined MDD of their foot-shoe model to avoid over emphasizing small differences that may have the potential of being interpreted as type I errors and determine the ability of the model to detect a true difference (e.g., reporting there is a difference between shod and unshod conditions when there actually is no difference; false-positive results). Researchers and clinicians should be aware that studies measuring dancers in shod conditions may not be accurate unless the authors explicitly report the steps taken to mitigate overestimations of joint motion and reduce the chance of committing type I errors.

Inter-segmental kinematics are critical for analyzing dance movement,⁴⁸ particularly the MTP joints¹⁰¹ and the midfoot,³⁵ to reduce the likelihood of measurement error due to violation of the rigid body assumption.⁶³ However, 15 of the 25 studies in the current literature review measured the foot as a single rigid body. There is little evidence that the marker sets used to evaluate dance-specific movement are adequately described to accurately measure the extreme total, segmental, and intersegment ROM exerted by dancers. Results from the dance-specific foot model studies reviewed support the use of multi-segment foot biomechanical foot models to precisely measure kinetics

and kinematics of the foot separate from the ankle during dance-specific movements.

Implications

The current literature review identified and evaluated studies that utilized 3D motion capture systems to analyze the in vivo biomechanics of the foot and ankle during dance-specific movement. Investigation into the kinematic measures and the kinetic forces placed on the foot and ankle during static and dynamic dance movement requires valid measurement tools that can evaluate joint motion in all three planes.⁵⁴ Future studies should aim to develop a methodological framework exclusive to dance-medicine research using 3D motion capture. The primary objectives of a methodological framework is to reduce inconsistencies between studies and promote repeatability of protocols. The present findings support the use of multi-segment foot models to evaluate the total, segmental, and intersegmental motion of the foot and ankle joints. By maintaining rigorous methodology through practices such as these, explicitly describing study protocols, and meticulously working to validate a biomechanical model with the capability of evaluating variables of interest, other researchers will be able to reproduce studies and advance the science of dance medicine.

Limitations

The review was limited to published, full-text articles and excluded studies presented at conferences or non-published dissertations that utilized 3D motion capture. Only studies published in the English language were reviewed, which may have limited the breadth of what has been published on the topic in other languages.

Conclusion

It is evident from the quality of the 3D foot models used in dance medicine research and the paucity of robust dance-specific measurement tools that this specialized area of research is in its developmental stages. The development of robust prevention and treatment techniques to reduce the prevalence of injury among dancers can only be accomplished when all of the significant factors related to the unchanging injury rates are known. Three-dimensional motion capture is a robust measurement tool that has the capability to assist researchers in evaluating the in vivo, inter-segmental motion of the foot and ankle to potentially discover many of the remaining significant factors predisposing dancers to injury.

References

- Russell JA, Kruse DW, Nevill AM, et al. Measurement of the extreme ankle range of motion required by female ballet dancers. *Foot Ankle Spec.* 2010;3(6):324-30.
- Carter S, Bryant A, Hopper L. Lower-leg and foot contributions to turnout in university-level female ballet dancers: a preliminary investigation. *J Am Podiatr Med Assoc.* 2017;107(4):292-8.
- Azevedo AM, Oliveira R, Vaz JR, Cortes N. Professional dancers distinct biomechanical pattern during multidirectional landings. *Med Sci Sports Exerc.* 2019;51(3):539-47.
- Russell JA, McEwan IM, Koutedakis Y, Wyon MA. Clinical anatomy and biomechanics of the ankle in dance. *J Dance Med Sci.* 2008;12(3):75-82.
- Carter SL, Bryant AR, Hopper LS. An analysis of the foot in turnout using a dance specific 3D multi-segment foot model. *J Foot Ankle Res.* 2019;12:10.
- Russell JA, Shave RM, Kruse DW, et al. Ankle and foot contributions to extreme plantar- and dorsiflexion in female ballet dancers. *Foot Ankle Int.* 2011;32(2):183-8.
- Wild CY, Grealish A, Hopper D. Lower limb and trunk biomechanics after fatigue in competitive female Irish dancers. *J Athl Train.* 2017;52(7):643-8.
- Dickson D, Hollman-Gage K, Ojofeitimi S, Bronner S. Comparison of functional ankle motion measures in modern dancers. *J Dance Med Sci.* 2012;16(3):116-25.
- Dozzi P, Winter D. Biomechanical analysis of the foot during rises to full pointe: implications for injuries to the metatarsal-phalangeal joints and shoe redesign. *Kinesiology and Medicine for Dance.* 1993;94(16):1.
- Kadel N, Boensisch M, Teitz C, Trepman E. Stability of Lisfranc joints in ballet pointe position. *Foot Ankle Int.* 2005;26(5):394-400.
- Fong Yan A, Hiller C, Sinclair PJ, Smith RM. Kinematic analysis of sautes in barefoot and shod conditions. *J Dance Med Sci.* 2014;18(4):149-58.
- Russell JA. Preventing dance injuries: current perspectives. *Open Access J Sports Med.* 2013;4:199-210.
- Yau RK, Golightly YM, Richardson DB, et al. Potential predictors of injury among pre-professional ballet and contemporary dancers. *J Dance Med Sci.* 2017;21(2):53-63.
- Gamboa JM, Roberts LA, Maring J, Fergus A. Injury patterns in elite preprofessional ballet dancers and the utility of screening programs to identify risk characteristics. *J Orthop Sports Phys Ther.* 2008;38(3):126-36.
- Luke AC, Kinney SA, D'Hemecourt PA, et al. Determinants of injuries in young dancers. *Med Probl Perform Art.* 2002;17(3):105-12.
- Cahalan R, Bargary N, O'Sullivan K. Pain and injury in elite adolescent Irish dancers: a cross-sectional study. *J Dance Med Sci.* 2018;22(2):91-9.
- Hincapie CA, Morton EJ, Cassidy JD. Musculoskeletal injuries and pain in dancers: a systematic review. *Arch Phys Med Rehabil.* 2008;89(9):1819-29.
- Jacobs CL, Hincapie CA, Cassidy JD. Musculoskeletal injuries and pain in dancers: a systematic review update. *J Dance Med Sci.* 2012;16(2):74-84.
- Steinberg N, Siev-Ner I, Peleg S, et al. Injuries in female dancers aged 8 to 16 years. *J Athl Train.* 2013;48(1):118-23.
- Davenport KL, Simmel L, Kadel N. Hallux valgus in dancers: a closer look at dance technique and its impact on dancers' feet. *J Dance Med Sci.* 2014;18(2):86-92.
- Bowerman E, Whatman C, Harris N, et al. Are maturation, growth and lower extremity alignment associated with overuse injury in elite adolescent ballet dancers? *Phys Ther Sport.* 2014;15(4):234-41.
- Ekegren CL, Quested R, Brodrick A. Injuries in pre-professional ballet dancers: incidence, characteristics and consequences. *J Sci Med Sport.* 2014;17(3):271-5.
- Russell JA, Yoshioka H. Assessment of female ballet dancers' ankles in the en pointe position using high field strength magnetic resonance imaging. *Acta Radiol.* 2016;57(8):978-84.
- Bowling A. Injuries to dancers: prevalence, treatment, and perceptions of causes. *Br J Sports Med.* 1989;298(6675):731-4.
- Hopper LS, Alderson JA, Elliott BC, Ackland TR. Dance floor force reduction influences ankle loads in dancers during drop landings. *J Sci Med Sport.* 2015;18(4):480-5.
- Pappas E, Orishimo KF, Kremenik I, et al. The effects of floor incline on lower extremity biomechanics during unilateral landing from a jump in dancers. *J Appl Biomech.* 2012;28(2):192-9.
- Reeve HK, Hopper LS, Elliott BC, Ackland TR. Lower limb kinematic variability in dancers performing drop landings onto floor surfaces with varied mechanical properties. *Hum Movement Sci.* 2013;32(4):866-74.
- Fong Yan A, Smith R, Vanwansseele B, Hiller C. Mechanics of jazz

- shoes and their effect on pointing in child dancers. *J Appl Biomech.* 2012;28(3):242-8.
29. Fong Yan A, Smith RM, Hiller CE, Sinclair PJ. Impact attenuation properties of jazz shoes alter lower limb joint stiffness during jump landings. *J Sci Med Sport.* 2017;20(5):464-8.
 30. Lobo da Costa PH, Azevedo Nora FGS, Vieira MF, et al. Single leg balancing in ballet: effects of shoe conditions and poses. *Gait Posture.* 2013;37(3):419-23.
 31. Nunes NMA, Haddad JJ, Bartlett DJ, Obright KD. Musculoskeletal injuries among young, recreational, female dancers before and after dancing in pointe shoes. *Pediatr Phys Ther.* 2002;14(2):100-6.
 32. 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):61-4.
 33. Quanbeck AE, Russell JA, Handley SC, Quanbeck DS. Kinematic analysis of hip and knee rotation and other contributors to ballet turnout. *J Sports Sci.* 2017;35(4):331-8.
 34. Krasnow D, Wilmerding M, Stecyk S, et al. Biomechanical research in dance: a literature review. *Med Probl Perform Art.* 2011;26(1):3-23.
 35. Carter SL, Sato N, Hopper LS. Kinematic repeatability of a multi-segment foot model for dance. *Sports Biomech.* 2018;17(1):48-66.
 36. Bruyneel AV, Mesure S, Pare JC, Bertrand M. Organization of postural equilibrium in several planes in ballet dancers. *Neurosci Lett.* 2010;485(3):228-32.
 37. Lin CF, Lee WC, Chen YA, Hsue BJ. Fatigue-induced changes in movement pattern and muscle activity during ballet relevé on demi-pointe. *J Appl Biomech.* 2016;32(4):350-8.
 38. Lin CF, Lee IJ, Liao JH, et al. Comparison of postural stability between injured and uninjured ballet dancers. *Am J Sports Med.* 2011;39(6):1324-31.
 39. Lin CF, Su FC, Wu HW. Ankle biomechanics of ballet dancers in relevé en pointe dance. *Res Sports Med.* 2005;13(1):23-35.
 40. Lin CW, Chen SJ, Su FC, et al. Differences of ballet turns (pirouette) performance between experienced and novice ballet dancers. *Res Q Exerc Sport.* 2014;85(3):330-40.
 41. Imura A, Iino Y. Comparison of lower limb kinetics during vertical jumps in turnout and neutral foot positions by classical ballet dancers. *Sports Biomech.* 2017;16(1):87-101.
 42. Imura A, Iino Y, Kojima T. Biomechanics of the continuity and speed change during one revolution of the Fouette turn. *Hum Movement Sci.* 2008;27(6):903-13.
 43. Ahonen J. Biomechanics of the foot in dance: a literature review. *J Dance Med Sci.* 2008;12(3):99-108.
 44. 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):1089-95.
 45. Bronner S, Ojofeitimi S. Gender and limb differences in healthy elite dancers: passe kinematics. *J Mot Behav.* 2006;38(1):71-9.
 46. Bronner S, Ojofeitimi S. Pelvis and hip three-dimensional kinematics in grand battement movements. *J Dance Med Sci.* 2011;15(1):23-30.
 47. Casabona A, Leonardi G, Aimola E, et al. Specificity of foot configuration during bipedal stance in ballet dancers. *Gait Posture.* 2016;46:91-7.
 48. Jarvis DN, Kulig K. Kinematic and kinetic analyses of the toes in dance movements. *J Sports Sci.* 2016;34(17):1612-8.
 49. Jarvis DN, Kulig K. Lower extremity biomechanical demands during saut de chat leaps. *Med Probl Perform Art.* 2016;31(4):211-7.
 50. Jarvis DN, Kulig K. Pointing the foot without sickling: an examination of ankle movement during jumping. *Med Probl Perform Art.* 2015;30(1):61-5.
 51. Jarvis DN, Smith JA, Kulig K. Trunk coordination in dancers and nondancers. *J Appl Biomech.* 2014;30(4):547-54.
 52. Rowley K, Jarvis D, Kurihara T, et al. Toe flexor strength, flexibility and function and flexor hallucis longus tendon morphology in dancers and non-dancers. *Med Probl Perform Art.* 2015;30(3):152-6.
 53. Kennedy JG, Collumbier JA. Bunions in dancers. *Clin Sports Med.* 2008;27(2):321-8.
 54. Donatelli RA. *The Biomechanics of the Foot and Ankle* (2nd ed). Philadelphia: F.A. Davis Company, 1996.
 55. Novella T. An easy way to quantify plantar flexion in the ankle. *J Back Musculoskelet Rehabil.* 1995;5(3):191-9.
 56. Novella TM. Simple techniques for quantifying choreographically essential foot and ankle extents of motion. *J Dance Med Sci.* 2004;8(4):118-22.
 57. Steinberg N, Hershkovitz I, Zeev A, et al. Joint hypermobility and joint range of motion in young dancers. *J Clin Rheumatol.* 2016;22(4):171-8.
 58. Deschamps K, Staes F, Roosen P, et al. Body of evidence supporting the clinical use of 3D multisegment foot models: a systematic review. *Gait Posture.* 2011;33(3):338-49.
 59. Qualisys. *Qualisys: QTM User Manual*. Gothenburg, Sweden, 2015.
 60. Bruening DA, Cooney KM, Buczek FL. Analysis of a kinetic multi-segment foot model. Part I: model repeatability and kinematic validity. *Gait Posture.* 2012;35(4):529-34.
 61. Leardini A, Benedetti MG, Berti L, et al. Rear-foot, mid-foot and fore-foot motion during the stance phase of gait. *Gait Posture.* 2007;25(3):453-62.
 62. Robertson G, Caldwell G, Hamill J, et al. *Research Methods in Biomechanics* (2nd ed). Champaign, Illinois: Human Kinetics, 2013.
 63. Nester CJ, Liu AM, Ward E, et al. Error in the description of foot kinematics due to violation of rigid body assumptions. *J Biomech.* 2010;43(4):666-72.
 64. Shultz R, Kedgley AE, Jenkyn TR. Quantifying skin motion artifact error of the hindfoot and forefoot marker clusters with the optical tracking of a multi-segment foot model using single-plane fluoroscopy. *Gait Posture.* 2011;34(1):44-8.
 65. Alcantara RS, Trudeau MB, Rohr ES. Calcaneus range of motion underestimated by markers on running shoe heel. *Gait Posture.* 2018;63:68-72.
 66. Arndt A, Wolf P, Liu A, et al. Intrinsic foot kinematics measured in vivo during the stance phase of slow running. *J Biomech.* 2007;40(12):2672-8.
 67. Maiwald C, Arndt A, Nester C, et al. The effect of intracortical bone pin application on kinetics and tibio-calcaneal kinematics of walking gait. *Gait Posture.* 2017;52:129-34.
 68. Nester C, Jones RK, Liu A, et al. Foot kinematics during walking measured using bone and surface mounted markers. *J Biomech.* 2007;40(15):3412-23.
 69. Miller E, Kaufman K, Kingsbury T, et al. Mechanical testing for three-dimensional motion analysis reliability. *Gait Posture.* 2016;50:116-9.
 70. Fong Yan A, Hiller C, Smith R, Vanwanseele B. Effect of footwear on dancers: a systematic review. *J Dance Med Sci.* 2011;15(2):86-92.
 71. Downs S, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *J Epidemiol Community Health.* 1998;52(6):377-84.
 72. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Practice* (3rd ed). Philadelphia: F.A. Davis Company, 2015.
 73. Abraham A, Dunskey A, Hackney ME, Dickstein R. Kinematic and kinetic analysis of repeated and static elevations in adolescent female dance students. *J Dance Med Sci.* 2018;22(1):33-43.
 74. Gontijo KN, Candotti CT, Feijo Gdos S, et al. Kinematic evaluation of the classical ballet step "plié." *J Dance Med Sci.* 2015;19(2):70-6.
 75. de Mello Viero CC, Kessler LP, Pinto C, et al. Height of the medial longitudinal arch during classical ballet steps. *J Dance Med Sci.* 2017;21(3):109-14.
 76. Kadel N, Donaldson-Fletcher E, Segal A, et al. Kinematic, kinetic, and electromyographic (EMG) analysis of muscle activity during rise to the pointe position. Presented at the 14th Annual Meeting of the International Association for Dance Medicine and Science, San Francisco, California, 2004.
 77. Lin CW, Su FC, Lin CF. Influence of ankle injury on muscle activation and postural control during ballet grand plié. *J Appl Biomech.*

- 2014;30(1):37-49.
78. Lin CW, Su FC, Wu HW, Lin CF. Effects of leg dominance on performance of ballet turns (pirouettes) by experienced and novice dancers. *J Sports Sci.* 2013;31(16):1781-8.
79. Rocha P, McClelland J, Sparrow T, Morris ME. The biomechanics and motor control of tap dancing. *J Dance Med Sci.* 2017;21(3):123-9.
80. Picon AP, Rodes CH, Bittar A, et al. Saute external rotation in beginner and advanced ballet dancers trained in different backgrounds: the turnout paradigm. *J Dance Med Sci.* 2018;22(4):218-24.
81. Chang M, O'Dwyer N, Adams R, et al. Whole-body kinematics and coordination in a complex dance sequence: differences across skill levels. *Hum Movement Sci.* 2020;69:102564.
82. Lee HH, Lin CW, Wu HW, et al. Changes in biomechanics and muscle activation in injured ballet dancers during a jump-land task with turnout (Sissonne Fermee). *J Sports Sci.* 2012;30(7):689-97.
83. Azevedo AM, Oliveira R, Vaz JR, Cortes N. Oxford foot model kinematics in landings: a comparison between professional dancers and non-dancers. *J Sci Med Sport.* 2020;23(4):347-52.
84. Lin CW, Lin CF, Hsue BJ, Su FC. A comparison of ballet dancers with different level of experience in performing single-leg stance on retire position. *Motor Control.* 2014;18(2):199-212.
85. Seo SG, Lee DY, Moon HJ, et al. Repeatability of a multi-segment foot model with a 15-marker set in healthy adults. *J Foot Ankle Res.* 2014;7(24):2-9.
86. Besier TF, Sturmeiks DL, Alderson JA, Lloyd DG. Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *J Biomech.* 2003;36(8):1159-68.
87. Caravaggi P, Benedetti MG, Berti L, Leardini A. Repeatability of a multi-segment foot protocol in adult subjects. *Gait Posture.* 2011;33(1):133-5.
88. Portinaro N, Leardini A, Panou A, et al. Modifying the Rizzoli foot model to improve the diagnosis of pes-planus: application to kinematics of feet in teenagers. *J Foot Ankle Res.* 2014;7(1):754.
89. Gorton GE 3rd, Hebert DA, Gannotti ME. Assessment of the kinematic variability among 12 motion analysis laboratories. *Gait Posture.* 2009;29(3):398-402.
90. Deschamps K, Staes F, Bruyninckx H, et al. Repeatability in the assessment of multi-segment foot kinematics. *Gait Posture.* 2012;35(2):255-60.
91. Bruening DA, Cooney KM, Buczek FL. Analysis of a kinetic multi-segment foot model. Part II: kinetics and clinical implications. *Gait Posture.* 2012;35(4):535-40.
92. Buczek FL, Walker MR, Rainbow MJ, et al. Impact of mediolateral segmentation on a multi-segment foot model. *Gait Posture.* 2006;23(4):519-22.
93. Hwang SJ, Choi HS, Lee KT, Kim YH. 3D motion analysis on the hallux valgus by using the multi-segment foot model. *Key Engineering Materials.* 2006;321-323, 988-991.
94. Saraswat P, Andersen MS, Macwilliams BA. A musculoskeletal foot model for clinical gait analysis. *J Biomech.* 2010;43(9):1645-52.
95. Sawacha Z, Cristoferi G, Guarneri G, et al. Characterizing multi-segment foot kinematics during gait in diabetic foot patients. *J Neuroeng Rehabil.* 2009;6:37.
96. Almeida MO, Davis IS, Lopes AD. Biomechanical differences of foot-strike patterns during running: a systematic review with meta-analysis. *J Orthop Sports Phys Ther.* 2015;45(10):738-55.
97. Knorz S, Kluge F, Gelse K, et al. Three-dimensional biomechanical analysis of rearfoot and forefoot running. *Orthop J Sports Med.* 2017;5(7):2325967117719065.
98. Stacoff A, Nigg B, Reinschmidt C, et al. Tibiocalcaneal kinematics of barefoot versus shod running. *J Biomech.* 2000;33(11):1387-95.
99. Bishop C, Paul G, Thewlis D. Recommendations for the reporting of foot and ankle models. *J Biomech.* 2012;45(13):2185-94.
100. Bishop C, Paul G, Thewlis D. The reliability, accuracy and minimal detectable difference of a multi-segment kinematic model of the foot-shoe complex. *Gait Posture.* 2013;37(4):552-7.
101. Goldmann JP, Sanno M, Willwacher S, et al. The potential of toe flexor muscles to enhance performance. *J Sports Sci.* 2013;31(4):424-33.