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

Kimberly P. Veirs, Andrew H. Fagg, Amgad M. Haleem, Lynn M. Jeffries, Ken Randall, Susan B. Sisson, and Carol P. Dionne

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. 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,
the dancer moves from end-range dorsiflexion (DF) into end-range plantar flexion (PF) of the ankle. Additionally, balancing in the demi-pointe relevé position transmits up to four times the dancer’s body weight through the foot. 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 [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 [12,14,55]. 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, strength, endurance, and motor control [19]) and variables extrinsically effecting the dancer (e.g., composition of dance floors [24-27] 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 [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 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 [1,4,6,7]. 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) [56]. More recently, dance medicine researchers are utilizing the 3D systems for analyzing dance-specific postures and movements [44].

### 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 [56]. 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 [55]. 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 [60,61,65]. As a result, they fail to capture all of the kinetic and kinematic contributions of the foot complex [58] and induce greater risk of measurement error because the inter-segmental bone movements in the foot are not considered. Three-dimensional multi-segment foot models (3DMMFs) 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 bone occurring whenever skin-mounted markers are used. 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. Maiwald et al. 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. 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° tracking difference for 35% of the parameters and > 5° 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. 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. 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.

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,
Table 1  Data Collection Instrument\textsuperscript{58,71,72}

<table>
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<tr>
<th>Question</th>
<th>Yes</th>
<th>No</th>
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<tbody>
<tr>
<td>1. Is the hypothesis, aim, and objective of the study clearly described?</td>
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<td>2. Are the main outcomes to be measured clearly described in the Introduction or Methods section?</td>
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<td>Purpose/specific aim(s)</td>
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<td>3. Are the characteristics of the participants included in the study clearly described?</td>
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<td>Number of participants:</td>
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<td>4. Are the variables of interest clearly described and operationally defined?</td>
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<td>Dependent variables:</td>
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<td>5. Is 3D motion capture the primary measurement tool used?</td>
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<td>System:</td>
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<td>Number of markers:</td>
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<td>Number of cameras:</td>
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<td>Measurement frequency:</td>
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<td>Additional device(s) used:</td>
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<td>6. Was the biomechanical model used sufficiently described?</td>
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<td>If yes, number of segments:</td>
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<td>Modeled foot segments:</td>
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<td>Barefoot or shoe used during data collection, type of shoe:</td>
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<td>7. Are the distributions of principal confounder, interaction, or effect modification variables described?</td>
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<td>If yes, what are they?</td>
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<td>8. Are the main findings of the study clearly described?</td>
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<td>9. Does the study provide estimates of the random variability in the data for the main outcomes?</td>
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<td>Non-normally distributed data: IQR</td>
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<td>Normally distributed data: SE, SD, or CI</td>
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<td>10. Have actual probability values been reported (e.g., 0.035 rather than &lt; 0.05) for the main outcomes except where the probability value is less than 0.001?</td>
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<td>Level of significance used:</td>
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<td>11. Were the statistical tests used to assess the main outcomes appropriate? (e.g., non-parametric tests used for small sample sizes)</td>
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<td><strong>External validity (generalizability)</strong></td>
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<td>12. Were the participants in the study representative of the entire population from which they were recruited?</td>
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<td>13. Can the results be generalized to other dancers, settings, or times?</td>
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<td><strong>Internal validity</strong></td>
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<td>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)?</td>
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<td>Describe:</td>
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<td>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”.</td>
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<td><strong>Validity of the measurement tool</strong></td>
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<td>16. Was validity of the measurement tool(s) described?</td>
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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. 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 segments and study methodology. 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.

### 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>
<thead>
<tr>
<th>Reliability</th>
<th>Yes</th>
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<tr>
<td>17. Was reliability measured? Test-retest reliability (ICC)</td>
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<td>18. Was a power analysis conducted a priori to determine sample size?</td>
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<td>19. Was Effect Size reported?</td>
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<td>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?</td>
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Table 2  Single-Segment Foot Models (N = 15), Study Design, Purpose, Specific Aims, Foot and Ankle Variables Measured, and Results

<table>
<thead>
<tr>
<th>Study</th>
<th>Study Design</th>
<th>Purpose and Specific Aim</th>
<th>Independent (I) and Dependent (D) Variables</th>
<th>Results</th>
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</table>
| Abraham et al. | 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 élevé among adolescent female dance students  
2. To investigate the relationships between élevé performance properties and participants’ demographics (age, height, weight, dancing experience, and leg dominance)  
3. To describe the relationships between kinematic properties in both élevé tasks | I: Two conditions of élevé task (feet parallel): repeated élevé and static élevé hold (balancing)  
D: Ankle kinematics: PF maximum angle and total PF ROM (deg) and kinetics: inter-leg WBD (percentage of body weight) | Repeated élevé: 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 élevé but linearly related |
| Chang et al.   | 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. | 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-plié, battement fondu à la secondé, pas jeté à la secondé, and grand jeté à la secondé  
D: Foot kinematics: midfoot longitudinal arch height (mm) | Arch height significantly reduced during battement fondu à la secondé, pas jeté à la secondé, and grand jeté à la secondé |
| Gontijo et al. | 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 plié (simultaneous hip, knee, and ankle flexion)  
2. To explore whether experienced ballet dancers respect those criteria when performing the plié | I: Plié movement (4 types): demi-plié in first position, grand plié in second position, and grand plié 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 plié described as uniform body weight distribution between the hallux, fifth toe, and heel |
| Hopper et al.  | 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 |

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<tr>
<th>Study</th>
<th>Study Design</th>
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<th>Independent (I) and Dependent (D) Variables</th>
<th>Results</th>
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</table>
| Imura et al.\(^{41}\)  | Descriptive, cross-sectional  | 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  | 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, elevé, pique passé (onto one foot), a two-foot spring up to pointe  
D: Ankle kinematics: PF and DF ROM (deg) and kinetics: joint moment (Nm) | Greatest PF ROM following elevé; when en pointe, regardless of movement: DF ankle moment occurs |
| Lin CF et al.\(^{39}\)  | Descriptive, cross-sectional  | 1. To investigate and establish the contribution of the ankle joint during the relevé en pointé 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 pointé 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  | 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  | 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  | To investigate how ankle sprains effect postural and muscular control during grand plié in ballet dancers  
(n\(_{\text{injured}}\) = 13; n\(_{\text{uninjured}}\) = 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 |
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<tr>
<th>Study</th>
<th>Study Design</th>
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<th>Independent (I) and Dependent (D) Variables</th>
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| Pappas et al. | 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<sub>males</sub> = 14; n<sub>females</sub> = 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<sup>-1</sup>) | 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.  | 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 quantitative 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.  | 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.   | 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<sup>-1</sup>) | Post-fatigue: sig dec ankle PF and greater ant shear and compressive ankle forces |
Six of the studies were of interest observed in static postures or during dance-specific movements. Five of the 25 studies utilized single-segment foot models,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 variables2 assessed during dance-specific movements.5,78,81 Two aforementioned studies were actually secondary data analyses29,40 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.55 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 dancers’77 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 3: Two-Segment Foot Models (N = 4), Study Design, Purpose, Specific Aims, Foot and Ankle Variables Measured, and Results

<table>
<thead>
<tr>
<th>Study</th>
<th>Study Design</th>
<th>Purpose and Specific Aim</th>
<th>Independent (I) and Dependent (D) Variables</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jarvis and Kulig48</td>
<td>Single-factor repeat measures, cross-sectional (N = 10)</td>
<td>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</td>
<td>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</td>
<td>Sig greater peak ext during relevé than the two jumps; Sig greater net joint moment during saut de chat leaps</td>
</tr>
<tr>
<td>Jarvis and Kulig49</td>
<td>Descriptive, cross-sectional (N = 30)</td>
<td>To compare biomechanical demands placed on the lower extremity joints during the takeoff and landing phases of saut de chat leaps</td>
<td>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</td>
<td>Sig greater joint moment at ankle and MPT during takeoff and at the hip during landing</td>
</tr>
<tr>
<td>Lee et al.82</td>
<td>Descriptive, cross-sectional (N = 22)</td>
<td>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)</td>
<td>I: Ankle injury condition: injured or not injured D: Ankle and foot kinematics: peak joint angles (deg)</td>
<td>Injured group: Sig greater peak ankle eversion angle, sig smaller hindfoot-to-tibial ever angle</td>
</tr>
<tr>
<td>Lin CF et al.83</td>
<td>Descriptive, test-retest (N = 20)</td>
<td>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</td>
<td>I: Fatigue condition: pre-fatigue and post-fatigue D: Ankle kinematics: joint angles (deg) in the sagittal, frontal, and transverse planes</td>
<td>Sig diff in ankle angle in all three planes during relevé</td>
</tr>
</tbody>
</table>
Table 4  Multi-Segment Foot Models (N = 6) , Study Design, Purpose, Specific Aims, Foot and Ankle Variables Measured, and Results

<table>
<thead>
<tr>
<th>Study</th>
<th>Study Design</th>
<th>Purpose and Specific Aim</th>
<th>Independent (I) and Dependent (D) Variables</th>
<th>Results</th>
</tr>
</thead>
</table>
| 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.⁵⁵             | Methodological reliability 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 plié, 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 ≥ 0.75) intra- and inter-assessor repeatably 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 sautés 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 sauté 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 sauté 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>
<thead>
<tr>
<th>Study</th>
<th>Dance Style</th>
<th>Movements Evaluated</th>
<th>Marker Set-Up</th>
<th>Measurement Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abraham et al.</td>
<td>Not specified</td>
<td>Elevé in sixth position (parallel)</td>
<td>BF</td>
<td>2 digital cameras for 3D motion capture; 2 independent force plates</td>
</tr>
<tr>
<td>Pappas et al.</td>
<td>Not specified (professional company dancers)</td>
<td>Single leg landing onto different inclined surfaces; male and female differences</td>
<td>Tennis shoes* (with no heel)</td>
<td>Eagle, 8-camera motion capture system; AMTI multicomponent force plate</td>
</tr>
<tr>
<td>Chang et al.</td>
<td>Latin Ballroom</td>
<td>Alternate Basic in Cha-Cha- Cha</td>
<td>Not specified (figures in pictorials are BF)</td>
<td>Cortex 3, 14-camera motion capture system</td>
</tr>
<tr>
<td>Gontijo et al.</td>
<td>Ballet</td>
<td>Demi-plié and grand plié in first and second positions</td>
<td>BF*</td>
<td>Four JVC video cameras and a 3D Peak Performance calibrator</td>
</tr>
<tr>
<td>Hopper et al.</td>
<td>Dancers from “performing arts’ school”</td>
<td>Drop landings on dance floors with various levels of force reduction</td>
<td>BF*</td>
<td>Vicon, 12-camera motion system; one AMTI force plate</td>
</tr>
<tr>
<td>Imura et al.</td>
<td>Ballet</td>
<td>Jumps with 1. Hips externally rotated/ turned out (TJ) 2. Hips parallel or neutral (NJ)</td>
<td>Soft ballet shoes; all of the same brand*</td>
<td>Vicon, 8-camera motion capture system; 2 force plates</td>
</tr>
<tr>
<td>Kadel et al.</td>
<td>Ballet</td>
<td>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</td>
<td>Pointe shoes* (Vicon plug-in marker set-up)</td>
<td>Vicon motion capture system</td>
</tr>
<tr>
<td>Lin CF et al.</td>
<td>Ballet</td>
<td>Relevé en pointe</td>
<td>Pointe shoes*</td>
<td>HIRES motion capture system; two force plates</td>
</tr>
<tr>
<td>Lin CW et al.</td>
<td>Ballet</td>
<td>Pirouettes (turns) en dehor (to right: clockwise turns; to left: counter-clockwise turns)</td>
<td>Soft ballet shoes*</td>
<td>Eagle, 8-camera motion capture system</td>
</tr>
<tr>
<td>Lin CW et al.</td>
<td>Ballet</td>
<td>Pirouettes (turns) en dehor (to right: clockwise turns; to left: counter-clockwise turns)</td>
<td>Soft ballet shoes*</td>
<td>Eagle, 8-camera motion capture system; two force plates</td>
</tr>
<tr>
<td>Lin CW et al.</td>
<td>Ballet</td>
<td>Grand plié in first position</td>
<td>Not specified* (ballet slippers pictured)</td>
<td>Eagle, 8-camera motion capture system; one force plate; surface EMG</td>
</tr>
<tr>
<td>Picon et al.</td>
<td>Ballet</td>
<td>Sauté in first position</td>
<td>BF</td>
<td>Optitrack FLEX: V100, 6 infrared cameras; one AMTI force plate</td>
</tr>
<tr>
<td>Wild et al.</td>
<td>Irish dance</td>
<td>Irish-dance leap</td>
<td>Soft Irish-dance shoes*</td>
<td>Vicon, 18-camera motion capture system; multi-channel force plate</td>
</tr>
<tr>
<td>Rocha et al.</td>
<td>Tap</td>
<td>Tap dance steps: 1. Nerve beats 2. Brush brush stamps 3. Heel ball walks</td>
<td>Tap shoes*</td>
<td>Vicon, 10-camera motion capture system</td>
</tr>
</tbody>
</table>

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

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

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

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

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

<table>
<thead>
<tr>
<th>Study</th>
<th>Dance Style</th>
<th>Movements Evaluated</th>
<th>Marker Set-Up</th>
<th>Measurement Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azevedo et al.</td>
<td>Not specified</td>
<td>Forward and lateral jump landings</td>
<td>BF</td>
<td>Vicon, 12-camera motion capture system</td>
</tr>
<tr>
<td>Carter et al.</td>
<td>Ballet</td>
<td>1. Parallel stance</td>
<td>BF</td>
<td>Vicon, 12-camera motion capture system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Turnout plié and stance</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>3. Turnout rise</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>4. Flex-point-fas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carter et al.</td>
<td>Ballet, modern</td>
<td>1. Functional turnout</td>
<td>BF</td>
<td>Vicon, 12-camera motion capture system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Forced turnout</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>3. Sautés in slightly open first</td>
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<tr>
<td>Fong Yan et al.</td>
<td>Jazz</td>
<td>Point-flex-point</td>
<td>BF (control condition) and 3 different jazz shoes (bony landmarks palpated through the shoe for marker placement on outside of shoe)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eagle and Cortex, 14-camera motion capture system; custom-built mechanical shoe dynamometer</td>
</tr>
<tr>
<td>Fong Yan et al.</td>
<td>Jazz</td>
<td>Sautés in second position</td>
<td>BF (control condition) and 4 different jazz shoes (bony landmarks palpated through the shoe for marker placement on outside of shoe)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eagle and Cortex, 14-camera motion capture system</td>
</tr>
<tr>
<td>Fong Yan et al.</td>
<td>Jazz</td>
<td>Sautés in second position</td>
<td>BF (control condition) and 3 different jazz shoes (bony landmarks palpated through the shoe for marker placement on outside of shoe)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14-camera motion analysis system; force platforms; custom-built mechanical shoe dynamometer</td>
</tr>
</tbody>
</table>
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, while four others assessed two variations of one type of movement (e.g., vertical jumps in two directions). The other 14 study protocols evaluated only one movement, including relevé (rising into demi-pointe or en pointe from plié), elevé (rising into demi-pointe or en pointe with straight legs), jump take-off and landing (e.g., sauté, saut de chat leaps, Sissonne Fermée), jump flex-point (open kinetic chain PF-DF-PF of the foot and ankle), and the Alternate Basic in the Cha-Cha-Cha.

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. 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), 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.

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, the Vicon plug-in, the Cleveland Clinic, and the Oxford Foot Model. Only four studies used a dance-specific biomechanical model with purposefully designed foot segments to analyze the dancers’ foot and ankle. 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, 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. Wild et al. referenced the University of Western Australia static lower limb marker set and stated they used a modification of the marker set placement. Hopper et al. reported parameters from a previous study analyzing gait: high repeatability for all sagittal plane kinematics (r² > 0.85) and high within- and between-tester reliability for DF and PF ROM (ICC > 0.85). Although Wild et al. referenced the original article pertaining to their model for the reader to reference and Hopper et al. 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., Fong Yan et al., and Jarvis and Kulig, 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. palpated the bony landmarks through the jazz shoes for marker placement on the outside of the shoe. In contrast, Lin et al. 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 other studies described how the markers should be placed.
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 seg-
ments to analyze inter-segmental movement of the foot.3,35,48,49
Jarvis and Kulig49 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 de-
mands 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 ana-
lizing 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.3 applied their modi-
ﬁed 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.3 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-par-
metric 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 of the other
studies used parametric testing even when the statistical con-
ditions 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.81 tested participants’ demographics, age, height,
and weight as possible confounding factors. Lin et al.77 did
not list specific interacting variables but reported that proper-
aites 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 (expo-
sure: 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 evi-
dence 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 mo-
tion capture system used for data collection (e.g., Qualisys™,
Vicon™, or Eagle™ systems). Carter et al.3,35 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.3 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, which is why the authors reported a broad range of inter-rater reliability across all variables tested.19 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 3DMMF’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.8788 Additionally, standardization of marker placement was found to reduce variability of measurement outcomes during gait by 20%.99 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.93 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,95 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.88,6162,6391-95 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 3DMMF 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.39 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 over estimations of joint motion and reduce the chance of committing type I errors.

Inter-segmental kinematics are critical for analyzing dance movement,35 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. 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**