Title:

Jumping in Ballet: A Systematic Review of Kinetic and Kinematic Parameters

Submission type: Systematic Review

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Preferred running head: The Kinetics and Kinematics of Jumping in Ballet

Number of figures and tables: 5 (1 figures; 4 tables)

Declarations

Contributors All authors contributed to the design of the systematic review, development of the search strategy, agreed the final studies for inclusion, reviewed and edited the manuscript, and approved the final version. AM and JS performed the electronic database searches. AM performed the critical appraisal of the included studies, data extraction of included studies, and wrote the first draft, and prepared all versions of the manuscript.

Funding and Conflicts of Interest This review did not receive funding to assist in its completion. The contributing authors have no conflict of interest to declare.

Abstract

Understanding the biomechanics of jumping in ballet dancers provides an opportunity to optimize performance and mitigate injury risk. This review aimed to summarize research investigating kinetics and kinematics of jumping in ballet dancers. PubMed (MEDLINE), SPORTDiscus, and Web of Science were systematically searched for studies published before December 2020. Studies were required to investigate dancers specializing in ballet, assess kinetics or kinematics during take-off or landing, and be published in English. A total of 3781 articles were identified, of which 29 met the inclusion criteria. Seven studies investigated take-off (kinetics: n = 6; kinematics: n = 4) and 23 studies investigated landing (kinetics: n = 19; kinematics: n = 12). Included articles were categorized into six themes: Activity Type (n = 10), Environment and Equipment (n = 10), Demographics (n = 8), Physical Characteristics (n = 3), Injury Status (n = 2), and Skill Acquisition and Motor Control (n = 1). Peak landing vertical ground reaction force (1.4–9.6 times body weight) was most commonly reported. Limited evidence suggests greater ankle involvement during the take-off of ballet jumps compared to countermovement jumps. There is also limited evidence indicating greater sagittal plane joint excursions upon landing in ballet dancers compared to non-dancers, primarily through a more extended lower extremity at initial contact. Only four articles investigated male ballet dancers which is a notable gap in the literature. The findings of this review can be used by dance science and medicine practitioners to improve their understanding of jumping in ballet dancers.

Key Words: Dance, Take-off, Landing, Biomechanics

1 Introduction

Ballet dancers complete a high rate of jumping actions, exceeding that observed in contemporary dance (1) and comparable to that observed in volleyball (2). Consistent with research in sport (3), repetitive or single effort jumping has been identified as a common mechanism of injury in ballet, with 25% of all time-loss injuries caused by jumping actions in professional ballet dancers (4). Moran et al. (5) suggested that activities with high volumes of jumping and landing should give further attention to the biomechanical analysis of such actions, as this can assist when planning and programming training cycles, as well as creating return-to-play criteria following injury (6,7). This is especially relevant in ballet given that classical ballet technique is characterized by lower extremity turnout, foot orientation across five classical positions, and an upright torso, which may affect the execution of jumping actions through altered kinetics and kinematics (8,9). Most research investigating jumping in dancers, however, has been conducted in non-ballet dancers or dancers of mixed cohorts including ballet, modern, jazz, hip hop, or other dance forms.

Biomechanical analysis of jumping has been used in sport and exercise literature to make inferences on injury risk, neuromuscular fatigue, and the determinants of vertical jumping performance (10–12). Much of the research investigating jumping in dance has examined the kinetics and kinematics of landing to reduce jump-related injuries that result from poor landing biomechanics (13–16). Dance research, however, has also investigated the influence of various internal (e.g., maturation (17), sex (18,19), and performance level (20)) and external (e.g., floor surface properties (21,22), footwear (23), and stage incline (24–26)) factors on jumping biomechanics during take-off and landing. The numerous factors that have been researched in dance illustrate the complexity of this subject area, as the results may be context-specific. To date, no comprehensive review describing the kinetic and kinematic characteristics of jumping in ballet dancers has been published. A review of this nature will provide dance science and medicine practitioners with a clear understanding of the research surrounding take-off and landing in dancers of this genre across a variety of contexts.

This study aimed to systematically review original research that has investigated the kinetics and kinematics of take-off and landing in ballet dancers and categorize the findings into context-specific themes.

2 Methods

2.1 Search Strategy and Study Selection

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis was used as a framework for this systematic review (27). An electronic search for original research was conducted within the databases PubMed (MEDLINE), SPORTDiscus, and Web of Science. All original research published prior to December 2020 was included. Boolean operators were used to formulate a string of keywords relating to either the activity or the subject area: (ballet OR ballerina OR dance OR dancing OR dancer) AND (jump OR landing OR plyometric OR impact OR "ground reaction force" OR power OR biomechanics OR kinetics OR kinematics OR leap OR "jump technique" OR "landing technique"). Titles, abstracts, and full texts were screened independently by two authors (AM & JS) to determine inclusion and a subgroup met (AM, JS, JT, PP, & DB) to discuss the final articles; any discrepancies between authors were resolved through consensus.

2.2 Eligibility Criteria

This review included original research that investigated the kinetics and kinematics of take-off or landing in ballet dancers. Participants of all performance levels were included. The inclusion criteria required research to investigate participants whose primary genre of dance was ballet, report one or more kinetic or kinematic outcome measures during either the take-off or landing phase of a jump, to be considered original research, and be published in English. Studies were excluded where participants were non-ballet dancers or dancers of multiple genres, where studies exclusively investigated biomechanical variables during flight, where studies investigated biomechanical variables that were not considered kinetics or kinematics, and where the format of research was a conference abstract/proceeding, PhD dissertation, letter, or review.

2.3 Methodological Quality

The AXIS tool was used by the lead reviewer (AM) to critically appraise study design, reporting quality, and risk of bias (28). The AXIS tool is made up of twenty questions across five sections that address the introduction (n = 1), methods (n = 10), results (n = 5), discussion (n = 2), and miscellaneous items (n = 2). A numerical scale was applied where 'yes' was classified as one and 'no' or 'do not know' were classified as zero, in line with previous research (29). Questions 7, 13, 14, and 15 were removed because they related to survey questionnaires and did not apply to the study design of included research; this allowed for a maximum score of 16.

2.4 Data Extraction

Data were extracted and tabulated under pre-defined headings by the lead reviewer (AM). Extracted data included subject characteristics (sex, performance level, dance genre, age, height, and mass), jump type, equipment (including sampling frequencies or frame rates), measures (kinetic or kinematic variables), and results. Where data were available in charts, they were extracted using WebPlotDigitizer 3.9 (30). Where data were unavailable, authors were contacted. Study cohorts were categorized based on sex, age, and professional status to facilitate interpretation. When ballet dancers were compared to other cohorts, the terms 'dancers from mixed genres' or 'non-dancers' were used. Age was categorized as pre-adolescent (≤ 9 years), adolescent (10–19 years), or adult (≥ 20 years) (31). Jump types were grouped as ballet-specific or non-specific. For example, a countermovement jump (CMJ) would be referred to as a non-specific jump, whereas a sauté would be referred to as a ballet-specific jump.

2.5 Themes

Six themes were used to facilitate the synthesis of results and discussion: Activity Type, Demographics, Equipment and Environment, Physical Characteristics, Skill Acquisition and Motor Control, and Injury Status. Activity Type included studies that manipulated variables such as limb position, contraction type, technique, or drop height. Demographics included studies that investigated factors such as age, sex, training history, or dance genre. Environment and Equipment included studies that investigated factors such as floor surface properties, floor inclination, shoe condition, or taping. Physical Characteristics included studies that investigated factors such as strength, physical training interventions, and fatigue resistance. Skill Acquisition and Motor Control included studies that investigated variables such as focus of attention, self-talk, and imagery. Injury Status included studies that investigated factors such as current or previous injury.

3 Results

3.1 Identification and Selection

A total of 3781 articles were identified after the initial search of three electronic databases. Following the removal of duplicates, the titles of 2568 articles were screened for suitability, 2462 of which were excluded. The abstracts of the remaining 107 articles were reviewed, of which 44 were excluded as they did not meet the inclusion criteria. An additional 7 articles were identified through hand searches. Full texts of the resulting 70 articles were inspected; 41 articles were excluded, leaving a total of 29 articles that met the inclusion criteria and were included in the systematic review (32–60; Figure 1).

<< Insert Figure 1 Around Here >>

3.2 Study Characteristics

A detailed overview of the results of the included studies is presented in Table 1. Twenty-one studies investigated ballet-specific jumps (32,34,37–39,41,43–45,47,49–53,55–60), six investigated non-specific jumps (33,36,40,42,46,48), and two investigated both ballet-specific and non-specific jumps (35,54). Appendix 1 provides a glossary of included ballet-specific jumps. Nineteen studies exclusively investigated female ballet dancers (33,36,39,41,43,44,46,48–50,52–60), two investigated males (40,45), two investigated males and females (38,47), and six did not specify the sex of participants (32,34,35,37,42,51). Fourteen studies investigated adults (35,39–44,47,49,50,54,55,57,59), ten investigated adolescents (33,36–38,46,48,53,56,58,60), one investigated a mix of adults and adolescents (32), and three did not specify the age of participants (34,45,51). Nine studies investigated professional ballet dancers (35,40,43,45,46,48,50,51,54), eighteen investigated non-professionals (32–34,36–39,41,42,44,49,52,55–60), and two investigated a mix of professionals and non-professionals (47,53).

<< Insert Table 1 Around Here >>

Seven studies investigated the take-off phase (kinetics: n = 6; kinematics: n = 4) and 23 studies investigated the landing phase (kinetics: n = 19; kinematics: n = 12) across various jumps (Table 2).

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Included articles were categorized into six themes to facilitate the synthesis of results: Activity type (n = 10), Environment and Equipment (n = 10), Demographics (n = 8), Physical Characteristics (n = 3), Injury Status (n = 2), and Skill Acquisitions and Motor Control (n = 1) (Table 3).

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3.3 Critical Appraisal

The mean (SD) critical appraisal score across included studies was 10.7 ± 3.7 out of 16 (Table 4). The highest scoring criteria was a "representative selection process" (n = 29), followed by a "clear identification of aims" (n = 26) and an "appropriate study design" (n = 25). The lowest scoring criteria were the "justification of sample size" (n = 3) and the "disclosure of funding sources or conflicts of interest" (n = 7).

<< Insert Table 4 Around Here >>

3.4 Kinetic Parameters

Six articles investigated kinetics during take-off and 19 articles investigated kinetics during landing (Table 2). Theoretical peak take-off power (~23–24 W·kg-1) and force (~22–24 N·kg-1) during a countermovement jump (46,48) and mean power during a Bosco repeated jump test (18 W·kg-1 (40)) were reported in professional ballet dancers. Perry et al. (49) reported peak vertical ground reaction force (vGRF), mean rate of force development (RFD), peak ankle joint moment, and peak power during take-off of a horizontal and vertical unilateral ballet-specific jump, demonstrating higher values during the horizontal take-off (Cohen's d > .80). Two articles investigated lower extremity joint moments, power, and work during bilateral jumps and reported a proximal-to-distal shift in take-off strategy between balletic and non-balletic jumps (35,54).

Twelve articles reported peak landing vGRF, two of which provided absolute vGRF (34,60). Seven articles investigated ballet-specific jumps reporting relative peak landing vGRF values between 1.4–9.6 times body weight (BW; 40–46), with the highest vGRFs (3.2–9.6 BW) observed during the grand jeté. Further, three articles investigated non-ballet jumps, reporting vGRF values between 2.7–5.0 BW (36,42,53). An additional two articles investigated vGRF but did not report any data (33,45). Five articles reported loading rate with values ranging between 9.5–222.7 BW·s-1 during a variety of ballet-specific landings (47,50,51,56,58); however, two studies used sample sizes of 1 (50) and 2 (51) participants. Two articles investigated lower extremity joint stiffness during ballet specific jumps, reporting the greatest values at the ankle (56) and knee (44). Three articles investigated total stiffness of the lower extremity; two of which used a single dataset (39,41).

3.5 Kinematic Parameters

Four articles investigated kinematics during take-off and 12 articles investigated kinematics during landing (Table 2). Reduced peak hip flexion, reduced mean anteroposterior rotation, and greater lower extremity external rotation is observed in turnout during take-off when compared to parallel (54). Theoretical take-off velocity was reported as 3.7–4.2 m·s-1 during CMJs in two articles (46,48). Ten articles reported peak lower extremity joint angles upon landing, typically demonstrating greater angles at the knee when compared to the ankle or the hip. Seven studies investigated ballet-specific jumps, reporting peak joint angles between 15.0–83.0° at the knee, -5.7–27.5° at the ankle, and 7.9–

59.7° at the hip (37,43,50,55–58). Three studies investigated non-specific jumps and reported peak joints angles between 54.0–79.8° at the knee, 25.2–60.5° at the ankle, and 29.1–62.8° at the hip (33,36,42). Two articles demonstrate that dancers display greater lower extremity excursions upon landing compared to non-dancers, primarily due to greater lower extremity extension at initial contact (33,36). Hackney et al. (55) reported slightly higher peak joint velocities at the ankle compared to the knee upon landing from an échappé sauté (512.6 ± 47.3 vs. 343.7 ± 86.1, respectively). Two articles investigated impact acceleration upon landing from ballet-specific jumps (43,53), one of which illustrated positive relationships between impact acceleration and peak landing vGRF (53).

3.6 Activity Type

Ten studies investigated the influence of different jumping and landing activities on the kinetics and kinematics of ballet dancers (Table 3). Reduced knee moments were observed during the take-off of a ballet jump when compared to a CMJ in two studies (35,54). Although not significant, greater ankle moments, power, and work were observed during CMJs compared to ballet jumps in both articles (35,54). Imura and Iino (54) also reported greater external rotation torque, greater thigh and foot external rotations, and smaller trunk and hip flexion angles during a sauté compared to a CMJ. One study reported greater vGRF, peak ankle moments, mean RFD, and peak ankle power during the take-off of a saut de chat compared to a temp levé (49).

McPherson, Schrader, and Docherty (52) observed greater peak landing vGRF during a grand jeté when compared to an assemblé (3.8 ± 0.9 vs. 3.3 ± 0.4 BW), even at lower jump heights. Similar findings were reported by Arnwine & Powell (47), who observed greater vGRF, loading rate, and vertical impulse during a grand jeté compared to a sauté. When landing en pointe, lower peak vGRF (531 ± 82 vs. 736 ± 96 N) and shorter times to peak landing vGRF are evident compared to landing on a flat foot (34). Gorwa et al. (50) investigated three different ballet jumps and reported greater landing vGRF and loading rate during a grand jeté compared to an entrelacé and a ballonné. Conversely, Gorwa et al. (50) observed greater ankle, knee, and hip moments upon landing from a ballonné, compared to an entrelacé and a grand jeté. Moreover, differences in peak joint angles were observed, with the greatest values for the ankle during the entrelacé, the knee during the ballonné, and the hip during the grand jeté; however, no statistical tests were performed and only one ballet dancer was investigated. Dworak et al. (51) reported 8 different ballet jumps demonstrating vGRF between 5.3–9.4 BW and loading rates between 26.2–128.5 BW·s-1, with the greatest values observed during the grand pas de chat; however, only two ballet dancers were investigated and their characteristics were poorly outlined. Critical appraisal scores ranged from 2-15 (Table 4).

3.7 Demographics

Six studies investigated kinetic and kinematic differences across demographics during take-off and landing in ballet dancers (Table 3). One study investigated force-velocity characteristics across company rank in female professional ballet dancers, reporting that soloists demonstrated greater theoretical take-off power compared to second soloists (48). Moreover, soloists and second soloists demonstrated greater theoretical take-off power and velocity compared to corps de ballet members. Professional ballet dancers have demonstrated lower mean power than both amateur and professional athletes during a Bosco repeated jump test (40). When ballet dancers have been compared to volleyball athletes, ballet dancers have demonstrated larger ankle moments, power, and work, although no statistical analysis was conducted (35). Critical appraisal scores ranged from 10-16 (Table 4).

Female adolescent non-professional ballet dancers show greater joint angles and excursions across multiple planes of motion when compared to adolescent non-dancers during unilateral drop landings; greater sagittal plane excursions were due to landing with a relatively extended lower limb (33,36). During bilateral drop landings, no differences were observed in sagittal plane ankle or knee joint angles between adult non-professional ballet dancers and non-dancers (42). Harwood et al. (33) observed reduced time to peak vGRF and greater hip extension moments during a horizontal hop, but not a vertical hop, in female adolescent non-professional ballet dancers when compared to non-dancers. In a mixed group of pre-professional and professional ballet dancers, females demonstrated greater peak landing vGRF, vertical impulse, and loading rate during a grand jeté but not a sauté when compared to males (47).

3.8 Environment and Equipment

Ten studies investigated the effects of environment and equipment on the kinetics and kinematics of take-off and landing in ballet dancers (Table 3), two of which reported the same data (41,59). When ballet flats and barefoot conditions have been investigated, no differences in peak landing vGRF were reported (45,52), whereas landing in pointe shoes has demonstrated smaller peak landing vGRF compared to ballet flats (1743 ± 253 vs. 1613 ± 262 N; 60). Character shoes, which have higher heel heights, increased sagittal plane knee excursions (64.1 ± 5.6 vs. 71.0 ± 4.3°) and reduced knee stiffness (34.8 ± 14.2 vs. 15.3 ± 7.6 Nmm·deg-1) compared to barefoot (44,57). Greater lower extremity stiffness values were reported when landing from a grand jeté and échappé sauté on a sprung floor compared to a stiff floor (39,41,59). Hackney et al. (55) observed reduced knee angles (55.2 ± 11.5° vs. 57.8 ± 9.6°) and ankle velocities (492 ± 50°·s-1 vs. 513 ± 47°·s-1) when performing échappé sautés on a sprung floor compared to a stiff floor. Mulligan taping decreased forces at the hip and knee upon landing from a ballet-specific jump when compared to no tape or Kinesiotape, with no changes in jump height, or hip and knee flexion angles (37). In two studies, no statistical tests were conducted (34,45). Critical appraisal scores ranged from 3–13 (Table 4).

3.9 Physical Characteristics

One study investigated the effects of a training intervention and two studies investigated the effects of a fatiguing protocol on kinetics and kinematics of take-off and landing in adolescent female ballet dancers (Table 3). Individualized training programs, based on force-velocity profiling, improve force-velocity imbalances in professional ballet dancers, primarily through increased force production during take-off (46). Almonroeder et al. (53) reported increased peak landing vGRF, loading rate, and acceleration across the duration of a dance-specific fatiguing protocol. Conversely, Peng et al. (56) documented no differences in peak landing vGRF during a fatiguing protocol, although, a distal-to-proximal shift in strategy was described under acute fatigue. The distal-to-proximal shift in strategy was characterized by an increase in hip stiffness and angular impulse, and reductions in knee moments, ankle joint excursions, and power (56). Critical appraisal scores ranged from 14–15 (Table 4).

3.10 Skill Acquisition and Motor Control

No differences were observed in kinematic variables following a mental imagery intervention in adult female professional ballet dancers (43). The critical appraisal score was 6/16 (Table 4).

3.11 Injury Status

Two studies investigated the influence of injury on kinetics and kinematics of take-off and landing in adolescent female non-professional ballet dancers (Table 3). Lee et al. (58) investigated previously injured and uninjured ballet dancers landing from a sissonne fermée finding no difference in peak landing vGRF, but lower loading rates (9.5 ± 1.9 vs. 11.0 ± 3.4 BW·s-1) and greater ankle eversion (11.9 ± 7.6 vs. 8.1 ± 2.9°) in previously injured dancers. Peng et al. (56) observed greater peak landing vGRF, knee joint power absorption, and patellofemoral joint stress, with no differences in joint excursions in female ballet dancers with patellofemoral pain compared to uninjured dancers. Study critical appraisal scores were 14 (58) and 15 (56) out of 16 (Table 4).

4 Discussion

This is the first study to comprehensively review research investigating the kinetics and kinematics of take-off and landing in ballet dancers. The most common kinetic variable assessed was peak landing vGRF which was almost two-fold greater during ballet-specific jumps compared to non-specific jumps, and greatest during the grand jeté. Loading rates were reported in five studies (9.5–222.7 BW·s-1), however, large ranges were observed, potentially due to small sample sizes and different technical demands across jumps (47,50,51,56,58). Peak sagittal plane joint angles were the most assessed kinematic with many studies demonstrating the greatest joint angles at the knee compared to the ankle and hip. However, broad ranges were observed which may be explained by differences in participant characteristics and methods of data collection. Two articles compared ballet-specific jumps to CMJs and provide limited evidence for a shift in strategy that favors the ankle over the hip during ballet jumps (35,54). There is limited evidence to suggest that ballet dancers demonstrate greater lower extremity joint excursions upon landing when compared to non-dancers, characterized by greater relative lower extremity extension upon landing (33,36). Male ballet dancers were exclusively investigated in two studies and investigated alongside female dancers in a further two studies. The lack of research investigating male ballet dancers is identified as a major gap in the research. Twenty-five of the included articles have investigated kinetics during take-off or landing, however, the majority lack a comprehensive analysis. The need for more research investigating kinetics results from methodological concerns within this research area, in-part identified by the critical appraisal scores (10.7 ± 3.7; range: 2–16). Due to the broad nature of this review, each identified theme outlined in the results is discussed independently.

4.1 Activity Type

Two articles investigated the influence of turnout, a key characteristic of classical ballet, providing limited evidence of reduced knee and hip, and greater ankle contributions to take-off kinetics (35,54). Greater lower extremity external rotation and smaller hip and trunk flexion were observed by Imua and Iino (54), which may be indicative of shorter posterior hip muscle lengths across both the sagittal and transverse planes. A shortened muscle length will influence the length-tension relationship and potential force production capacity of a muscle (61,62). Although no differences in hip extensor torque were observed in professional ballet dancers between a CMJ in parallel and turnout (54), smaller hip moments, power, and work have been observed in professional dancers when compared to professional volleyball athletes (35). There is limited evidence to suggest that turnout may result in a proximal-to-distal shift in joint contributions during take-off.

McPherson et al. (52) investigated unilateral and bilateral ballet jumps, observing greater peak landing vGRF during a grand jeté compared to an assemblé. Arnwine and Powell (47), reported similar data, supporting the findings of greater landing vGRFs in unilateral landings. Conversely, Pappas et al. (63) investigated both unilateral and bilateral drop landings in recreational athletes, finding no difference in peak landing vGRF (3.2 ± 1.3 vs. 2.7 ± 1.3 BW, respectively). The differences observed in ballet dancers may not be comparable to athletes due to the unique technical requirements across different classical ballet jumps. Landing biomechanics of various ballet jumps were reported in two studies (50,51), providing a range of landing vGRFs, loading rates, moments, and joint ranges of motion. However, studies were underpowered or no statistical tests were conducted and methodological issues were apparent (Table 4) making the interpretation challenging.

Perry et al. (49), however, demonstrated greater peak vGRF, mean RFD, and peak ankle moments and power during the take-off of a unilateral horizontal ballet jump compared to a vertical ballet jump.

Chockley (34) investigated landing vGRF en pointe and on a flat foot, however, landing phases were poorly defined making a comparison between the two positions challenging. Further research is required to investigate kinetic and kinematic differences across different jumping activities in ballet dancers using previously published methods to quantify variables of interest (64,65).

4.2 Demographics

No sex differences in the rate of jumping during a performance (1) or injury as a consequence of jumping activities (4) have been reported in ballet dancers. Nonetheless, nineteen studies exclusively investigated female ballet dancers. Greater lower extremity joint angles and excursions were observed in female adolescent ballet dancers when compared to non-dancers during unilateral drop landings, explained in part through greater extension upon landing (33,36). Greater lower extremity extension upon landing has been previously cited as an injury risk factor, due to increased lower extremity stiffness (66), however, greater extension prior to landing has been associated with both stiff and compliant landings (66,67). Due to the more compliant landings observed in both of the included studies, greater extension at initial contact is likely a result of the technical requirements of ballet (33,36). Anecdotally, an extended lower extremity is deemed more aesthetically pleasing but may pose challenges to ballet dancers when coordinating the time that they permit the lower extremity to flex.

Knee valgus and high landing vGRF have been associated with a greater risk of ACL injury, especially in female populations (18). Knee valgus patterns were present in adolescent female ballet dancers, but not non-dancers in two studies (33,36), and one study identified greater vGRF in female ballet dancers when compared to their male counterparts (47). Greater neuromuscular control may therefore be required in female and adolescent populations to ensure they are able to maintain optimal alignment and minimize vGRF during landing activities. Adult dancers of mixed genres have demonstrated potentially safer landing kinematics when compared to non-dancers (68), as well as improved ability to maintain external rotation during take-off and landing when compared to adolescent and adult ballet dancers (32). It is plausible that early specialization in one dance genre, such as ballet, may lead to reduced athletic development in place of technical advancement (69).

No differences in relative peak landing vGRF have been observed between adult or adolescent ballet dancers and non-dancers during various landing tasks (33,36,42). The lack of significant differences across adolescent ballet dancers and non-dancers may be attributed to relatively similar training backgrounds (70). It is only when ballet dancers engage in pre-professional or professional training that rehearsal volume significantly increases (4,71); it is likely at this point the volume of jumping increases and notable technical improvement in the form of landing biomechanics, such as reduced vGRF, is observed (16).

4.3 Environment and Equipment

Greater landing vGRFs are observed when landing in pointe shoes compared to ballet flats, however, force data were not reported relative to body weight (60). No differences in landing vGRF were observed between ballet flats and barefoot (45,52). Footwear has shown no effect on peak landing vGRF in athletes, except in the instance of unanticipated landings (72–75). However, none of these studies has compared shod conditions to barefoot. When barefoot and shod conditions have been compared in non-dancers, greater relative peak landing vGRF was observed under a barefoot condition (76). When landing in character shoes, increased knee excursions and reduced knee stiffness is observed compared to barefoot (44,57). In athletic populations, increasing heel heights have been shown to reduce vGRF and increase the speed of lower extremity muscle activation (77,78). The increased compliance at the knee when landing in character shoes is likely a consequence of the greater available sagittal plane range of motion at the ankle from the raised heel.

Ballet footwear has a limited capacity to absorb energy, likely due to the minimal nature of its construction, however, many studios and stage floors are sprung. Consistent floor surface properties are important, as training on floors with variable force reduction properties has been linked to a greater risk of injury in dancers (79). During ballet jumps, greater lower-limb stiffness, and smaller knee angles and ankle velocities are observed on a sprung floor compared to a stiff floor (39,41,55,59). Similar findings have been documented in dancers from mixed genres, where sprung surfaces with greater force reduction properties have led to reduced ankle velocities, joint moments, and negative power (22). Where variable floor surface has been associated with injury, no direct link has been made between either stiff or sprung floors and injury. Hopper et al. (22), postulated that traditional hard flooring requires greater neuromuscular control which may be associated with injury in dancers.

4.4 Physical Characteristics

Increasingly, ballet dancers engage in supplementary training to improve physical characteristics such as muscular strength and fatigue resistance to facilitate their preparation (80). Individualized training programs improve force-velocity imbalances in professional ballet dancers, primarily through increased force production during take-off (46). Strength training interventions may be a successful strategy to develop force production during take-off in ballet dancers as supplementary training is still not widely adopted in this population. Owing to the high rates of jumping during a performance, lower extremity fatigue resistance is of interest in ballet dancers (1,15). Inconsistent findings are reported in peak landing vGRF responses to a fatigue protocol in ballet dancers (53,56). Greater fatigue resistance of the ankle plantar flexors may optimize performance and minimize compensatory tissue loading due to the distal-to-proximal shift in strategy observed in one study (56). Jayalath et al. (81) has previously identified an association between fatigue, reduced ankle excursions, and reduced ankle power during landing activities in athletic populations and highlighted potential implications for injury.

4.5 Skill Acquisition and Motor Control

We identified one study that investigated the effect of focus of attention during take-off and landing in ballet dancers. No differences were observed in kinematic variables, potentially due to ambiguous cues that encompassed both an internal and external focus of attention (43). Previous research in non-dance populations has demonstrated that an external focus of attention results in improved stretch-shortening cycle performance during a drop jump and reducing vGRF during landing activities when compared to an internal focus of attention (82,83). There is scope for further research investigating motor learning and skill acquisition techniques such as self-talk, mental imagery, and focus of attention during take-off and landing activities in ballet dancers.

4.6 Injury Status

Current and previous lower extremity injury results in altered landing biomechanics when compared to uninjured ballet dancers (56,58), however, the altered landing biomechanics are not consistent across the two diagnoses that were investigated. Understanding how current and previous injury affects a dancer's kinetics and kinematics during jumping can facilitate the development of objective criteria when creating return-to-dance pathways in applied settings (84,85). Comprehensive return-to-play criteria exist within sport, facilitating a graded rehabilitation, and should serve as a framework when developing return-to-dance pathways (86). Consideration of jumping within return-to-dance pathways is especially important in ballet due to the frequency and intensity of such actions during performance (1).

4.7 Limitations

One limitation of the present review is that the participant age and performance level are broad, ranging from adolescent non-professional dancers to adult professional dancers. A broad range of ages and performance levels makes the application of findings across demographics challenging. The majority of research exists within a female, non-professional setting, which may not reflect the demographics that possess the resources to implement some of the findings of this review into performance or rehabilitation pathways. Another limitation of the present review is that many studies reported the same variables (e.g., peak joint angles) measured using different equipment (e.g., two-dimensional and three-dimensional motion capture). The use of different equipment may explain the large ranges observed across kinetic and kinematic variables that were reported across multiple studies.

4.8 Future Directions

The range in critical appraisal scores and lack of replication studies reveals several areas requiring further investigation. Sample size calculations and declarations outlining conflicts of interest were areas within the critical appraisal that were commonly missed by included studies. Moreover, several studies did not adequately report methodologies such that research could be replicated, with data pertaining to equipment sampling frequencies or inter and intra-set rest durations omitted (Table 1). Future research should consider utilizing critical appraisal checklists as a framework when constructing research designs and reporting methodologies. On several occasions, methodologies were utilized that had not been appropriately validated. For example, two-dimensional video analysis was used to calculate lower extremity joint angles during jumps in an externally rotated position. A large percentage of studies has been exclusively conducted on female and non-professional ballet dancers. Further research should aim to investigate both male and female ballet dancers across jumping activities to ensure a comprehensive understanding of kinetics and kinematics. The primary variables and phases of jumping actions that have been investigated are kinetics during landing (Table 2). Future research may wish to utilize previously reported methods to investigate jump phases more comprehensively in ballet dancers.

5 Conclusion

This study has comprehensively reviewed the literature investigating the kinetics and kinematics of take-off and landing phases in ballet dancers. We have identified peak landing vGRF as the most investigated variable in ballet dancers, across both ballet-specific jumps (1.4–9.6 BW) and non-specific jumps (2.7–5.0 BW). Kinematic findings suggest greater sagittal plane joint angles are observed at the knee when compared to the hip and ankle upon landing from both specific and non-specific jumps. Limited evidence exists to suggest there is greater ankle involvement during the take-off of ballet jumps compared to a CMJ. There is also limited evidence supporting greater lower extremity sagittal plane joint excursions in ballet dancers when compared to non-dancers, primarily due to greater lower extremity extension prior to landing. Much of the available research has investigated female ballet dancers, which may not be generalizable to male dancers, and is subsequently an area for future research. The range of quality assurance scores, and limited research within themes, reveals several areas for consideration such as power calculations and declarations expressing conflicts of interest. The findings of this review can be used by dance science and medicine practitioners to improve their understanding of jumping in ballet dancers.

References

1. Wyon M, Twitchett E, Angioi M, Clarke F, Metsios G, Koutedakis Y. Time motion and video analysis of classical ballet and contemporary dance performance. Int J Sports Med. 2011;32(11):851–5. 10.1055/s-0031-1279718

2. Maciel Rabello L, Zwerver J, Stewart RE, van den Akker-Scheek I, Brink MS. Patellar tendon structure responds to load over a 7-week preseason in elite male volleyball players. Scand J Med Sci Sport. 2019;29(7):992–9. 10.1111/sms.13428

3. Verhagen EALM, Van Der Beek AJ, Bouter LM, Bahr RM, Van Mechelen W. A one season prospective cohort study of volleyball injuries. Br J Sports Med. 2004;38(4):477–81. 10.1136/bjsm.2003.005785

4. Allen N, Nevill A, Brooks J, Koutedakis Y, Wyon M. Ballet injuries: Injury incidence and severity over 1 year. J Orthop Sports Phys Ther. 2012;42(9):781–90. 10.2519/jospt.2012.3893

5. Moran LR, Hegedus EJ, Bleakley CM, Taylor JB. Jump load: Capturing the next great injury analytic. Br J Sports Med. 2019;53(1):8–9. 10.1136/bjsports-2018-099103

6. Jiménez-Reyes P, Samozino P, Brughelli M, Morin JB. Effectiveness of an individualized training based on force-velocity profiling during jumping. Front Physiol. 2017;7:1–13. 10.3389/fphys.2016.00677

7. Dingenen B, Gokeler A. Optimization of the return-to-sport paradigm after anterior cruciate ligament reconstruction: A critical step back to move forward. Sport Med. 2017;47(8):1487–500. 10.1007/s40279-017-0674-6

8. Gilbert C, Gross M, Klug K. Relationship between hip external rotation and turnout angle for the five classical ballet positions. J Orthop Sport Phys Ther. 1998;27(5):339–47.

9. Masso N, German A, Rey F, Costa LL, Romero D, Guitarr S. Study of Muscle Activity During Releve in First and Sixth Positions. J Danc Med Sci. 2004;8(4):101–7.

10. Bisseling RW, Hof AL, Bredeweg SW, Zwerver J, Mulder T. Are the take-off and landing phase dynamics of the volleyball spike jump related to patellar tendinopathy? Br J Sports Med. 2008;42(6):483–9. 10.1136/bjsm.2007.044057

11. McErlain-Naylor S, King M, Pain MT homa. G. Determinants of countermovement jump performance: a kinetic and kinematic analysis. J Sports Sci. 2014;32(19):1805–12. 10.1080/02640414.2014.924055

12. Gathercole R, Sporer B, Stellingwerff T, Sleivert G. Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. Int J Sports Physiol Perform. 2015;10(1):84–92. 10.1123/ijspp.2013-0413

13. Orishimo KF, Kremenic IJ, Pappas E, Hagins M, Liederbach M. Comparison of landing

biomechanics between male and female professional dancers. Am J Sports Med. 2009;37(11):2187–93. 10.1177/0363546509339365

14. Orishimo KF, Liederbach M, Kremenic IJ, Hagins M, Pappas E. Comparison of landing biomechanics between male and female dancers and athletes, part 1: Influence of sex on risk of anterior cruciate ligament injury. Am J Sports Med. 2014;42(5):1082–8. 10.1177/0363546514523928

15. Liederbach M, Kremenic IJ, Orishimo KF, Pappas E, Hagins M. 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. 10.1177/0363546514524525

16. Ward R, Fong Yan A, Orishimo K, Kremenic I, Hagins M, Liederbach M, et al. Comparison of lower limb stiffness between male and female dancers and athletes during drop jump landings. Scand J Med Sci Sport. 2019;29(1):71–81. 10.1111/sms.13309

17. Fort-Vanmeerhaeghe A, Benet A, Mirada S, Montalvo AM, Myer GD. Sex and maturation differences in performance of functional jumping and landing deficits in youth athletes. J Sport Rehabil. 2019;28(6):606–13. 10.1123/jsr.2017-0292

18. Hewett TE, Myer GD, Ford KR, Heidt RS, Colosimo AJ, McLean SG, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. Am J Sports Med. 2005;33(4):492–501. 10.1177/0363546504269591

19. McMahon J, Rej S, Comfort P. Sex differences in countermovement jump phase characteristics. Sports. 2017;5(1):8. 10.3390/sports5010008

20. Pehar M, Sekulic D, Sisic N, Spasic M, Uljevic O, Krolo A, et al. Evaluation of different jumping tests in defining position-specific & performance-level differences in high level basketball players. Biol Sport. 2017;34(3):263–72. 10.5114/biolsport.2017.67122

21. 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 Mov Sci. 2013;32(4):866–74. 10.1016/j.humov.2013.07.009

22. 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. 10.1016/j.jsams.2014.07.001

23. Mikkelsen P, Jarvis DN, Kulig K. Heeled shoes increase knee work demand during repeated hopping in dancers. Med Probl Perform Art. 2018;33(4):243–50. 10.21091/mppa.2018.4036

24. Hagins M, Pappas E, Kremenic I, Orishimo KF, Rundle A. The effect of an inclined landing surface on biomechanical variables during a jumping task. Clin Biomech. 2007;22(9):1030–6.

10.1016/j.clinbiomech.2007.07.012

25. Pappas E, Orishimo KF, Kremenic I, Liederbach M, Hagins M. 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. 10.1136/bmj.298.6675.731

26. Pappas E, Kremenic I, Liederbach M, Orishimo KF, Hagins M. Time to stability differences between male and female dancers after landing from a jump on flat and inclined floors. Clin J Sport Med. 2011;21(4):325–9. 10.1097/JSM.0b013e31821f5cfb

27. Moher D, Shamseer L, Clarke M, Ghersi D, Liberati A, Petticrew M, et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst Rev. 2015;4(1):1–25. 10.1186/2046-4053-4-1

28. Downes MJ, Brennan ML, Williams HC, Dean RS. Development of a critical appraisal tool to assess the quality of cross-sectional studies (AXIS). BMJ Open. 2016;6(12):1–7. 10.1136/bmjopen-2016-011458

29. Coundouris SP, Terrett G, Laakso L, Schweitzer D, Kneebone A, Rendell PG, et al. A meta-analytic review of prospection deficits in Parkinson's disease. Neurosci Biobehav Rev. 2020;108:34–47. 10.1016/j.neubiorev.2019.10.016

30. Rohatgi A. WebPlotDigitizer Version 3.9 [Internet]. Available at: https://automeris.io/WebPlotDigitizer/. 2015 [cited 2020 Jun 16].

31. Canadian Paediatric Society. Age limits and adolescents. Paediatr Child Health. 2003;8(9):577–577. 10.1093/pch/8.9.577

32. Picon AP, Rodes CH, Bittar A, Cantergi D, Loss J, Sacco ICN. Sauté external rotation in beginner and advanced ballet dancers trained in different backgrounds the turnout paradigm. J Danc Med Sci. 2018;22(4):218–24. 10.12678/1089-313X.22.4.218

33. Harwood A, Campbell A, Hendry D, Ng L, Wild CY. Differences in lower limb biomechanics between ballet dancers and non-dancers during functional landing tasks. Phys Ther Sport. 2018;32:180–6. 10.1016/j.ptsp.2018.05.005

34. Chockley C. Ground reaction force comparison between jumps landing on the full foot and jumps landing en pointe in ballet dancers. J Dance Med Sci. 2008;12(1):5–8.

35. Ravn S, Voigt M, Simonsen EB, Alkjaer T, Bojsen-Moller F, Klausen K. Choice of jumping strategy in two standard jumps, squat and countermovement jump - effect of training background or inherited preference? Scand J Med Sci Sports. 1999;9(4):201–8. 10.1111/j.1600-0838.1999.tb00234.x

36. Hendry D, Campbell A, Ng L, Harwood A, Wild C. The difference in lower limb landing kinematics between adolescent dancers and non-dancers. J Danc Med Sci. 2019;23(2):72–9. 10.12678/1089-313X.23.2.72

37. Hendry D, Campbell A, Ng L, Grisbrook T, Hopper D. Effect of Mulligan's and Kinesio knee taping on adolescent ballet dancers knee and hip biomechanics during landing. Scand J Med Sci Sport. 2015;25(6):888–96. 10.1111/sms.12302

38. Mertz L, Docherty C. Self-described differences between legs in ballet dancers: do they relate to postural sability and ground reaction force measures? J Danc Med Sci. 2012;16(4):154–60.

39. Hackney J, Brummel S, Jungblut K, Edge C. The effect of sprung (suspended) floors on leg stiffness during grand jeté landings in ballet. J Danc Med Sci. 2011;15(3):128–33.

40. Kirkendall DT, Street GM. Mechanical jumping power in athletes. Br J Sports Med. 1986;20(4):163–4. doi: 10.1136/bjsm.20.4.163

41. Hackney J, Brummel S, Jungblut K, Edge C, Becker D, Chenoweth A, et al. Follow-up study to "The effect of sprung (suspended) floors on leg stiffness during grand jeté landings in ballet". J Danc Med Sci. 2011;15(3):134–5.

42. Volkerding KE, Ketcham CJ. Biomechanics and proprioceptive differences during drop landings between dancers and non-dancers. Int J Exerc Sci. 2013;6(4):289–99.

43. Couillandre A, Lewton-Brain P, Portero P. Exploring the effects of kinesiological awareness and mental imagery on movement intention in the performance of demi-plié. J Dance Med Sci. 2008;12(3):91–8.

44. 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. 2016;20(5):464–8. 10.1016/j.jsams.2016.09.011

45. Miller CD, Paulos LE, Parker RD, Fishell M. The ballet technique shoe: A preliminary study of eleven differently modified ballet technique shoes using force and pressure plates. Foot Ankle Int. 1990;11(2):97–100. 10.1177/107110079001100207

46. Escobar Álvarez JA, Fuentes García J, Da Conceição F, Jiménez-Reyes P. Individualized training based on force–velocity profiling during jumping in ballet dancers. Int J Sports Physiol Perform. 2019;1–7. 10.1123/ijspp.2019-0492

47. Arnwine RA, Powell DW. Sex Differences in Ground Reaction Force Profiles of Ballet Dancers During Single- and Double-Leg Landing Tasks. J Danc Med Sci. 2020;24(3):113–7. 10.12678/1089-313X.24.3.113

48. Escobar Álvarez JA, Reyes PJ, Pérez Sousa MÁ, Conceição F, Fuentes García JP. Analysis of the force-velocity profile in female ballet dancers. J Danc Med Sci. 2020;24(2):59–65. 10.12678/1089-313X.24.2.59

49. Perry SK, Buddhadev HH, Brilla LR, Suprak DN. Mechanical Demands at the Ankle Joint During Saut de Chat and Temps levé Jumps in Classically Trained Ballet Dancers</p>. Open Access J Sport Med. 2019;Volume 10:191–7. 10.2147/oajsm.s234289

50. Gorwa J, Michnik RA, Nowakowska-Lipiec K, Jurkojć J, Jochymczyk-Woźniak K. Is it possible to reduce loads of the locomotor system during the landing phase of dance figures? Biomechanical analysis of the landing phase in Grand Jeté, Entrelacé and Ballonné. Acta Bioeng Biomech. 2020;21(4). 10.37190/abb-01429-2019-02

51. Dworak LB, Gorwa J, Kmiecik K, Mączyński J. A study characterizing dynamic overloads of professional dancers. Biomechanical approach. Acta Bioeng Biomech. 2006;7(1):77–84.

52. McPherson AM, Schrader JW, Docherty CL. Ground reaction forces in ballet differences resulting from footwear and jump conditions. J Danc Med Sci. 2019;23(1):34–9. 10.12678/1089-313X.23.1.34

53. Almonroeder TG, Benson L, Madigan A, Everson D, Buzzard C, Cook M, et al. Exploring the potential utility of a wearable accelerometer for estimating impact forces in ballet dancers. J Sports Sci. 2019;38(2):231–7. 10.1080/02640414.2019.1692413

54. Imura A, Iino Y. Comparison of lower limb kinetics during vertical jumps in turnout and neutral foot positions by classical ballet dancers. Sport Biomech. 2017;16(1):87–101. 10.1080/14763141.2016.1205122

55. Hackney J, Brummel S, Newman M, Scott S, Reinagel M, Smith J. Effect of reduced stiffness dance flooring on lower extremity joint angular trajectories during a ballet jump. J Danc Med Sci. 2015;19(3):110–7. 10.12678/1089-313X.19.3.110

56. Peng HT, Chen WC, Kernozek TW, Kim K, Song CY. Influences of patellofemoral pain and fatigue in female dancers during ballet jump-landing. Int J Sports Med. 2015;36(9):747–53. 10.1055/s-0035-1547220

57. Fong Yan A, Hiller C, Sinclair PJ, Smith RM. Kinematic Analysis of Sautés in Barefoot and Shod Conditions. J Danc Med Sci. 2014;18(4):149–58. 10.12678/1089-313x.18.4.149

58. Lee HH, Lin CW, Wu HW, Wu TC, Lin CF. Changes in biomechanics and muscle activation in injured ballet dancers during a jump-land task with turnout (Sissonne Fermée). J Sports Sci. 2012;30(7):689–97. 10.1080/02640414.2012.663097

59. Hackney J, Brummel S, Becker D, Selbo A, Koons S, Stewart M. Effect of sprung (suspended) floor on lower extremity stiffness during a force-returning ballet jump. Med Probl Perform Art. 2011;26(4):195–9.

60. 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.

61. Ward S, Winters T, Blemker S. The architectural design of the gluteal muscle group: Implications for movement and rehabilitation. J Orthop Sports Phys Ther. 2010;40(2):95–102. 10.2519/jospt.2010.3302

62. Worrell TW, Karst G, Adamczyk D, Moore R, Stanley C, Steimel B, et al. Influence of joint

position on electromyographic and torque generation during maximal voluntary isometric contractions of the hamstrings and gluteus maximus muscles. J Orthop Sports Phys Ther. 2001;31(12):730–40. 10.2519/jospt.2001.31.12.730

63. Pappas E, Hagins M, Sheikhzadeh A, Nordin M, Rose D. Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. J Sport Med. 2007;17(4):263–8. 10.1097/JSM.0b013e31811f415b

64. Chavda S, Bromley T, Jarvis P, Williams S, Bishop C, Turner AN, et al. Force-time characteristics of the countermovement jump: Analyzing the curve in excel. Strength Cond J. 2018;40(2):67–77. 10.1519/SSC.0000000000000353

65. McMahon J, Suchomel T, Lake J, Comfort P. Understanding the key phases of the countermovement jump force-time curve. Strength Cond J. 2018;40(4):96–106. 10.1519/SSC.0000000000000375

66. Huston LJ, Vibert B, Ashton-Miller JA, Wojtys EM. Gender differences in knee angle when landing from a drop-jump. Am J Knee Surg. 2001;14(4):215–20.

67. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Steadman JR. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. Clin Biomech. 2003;18(7):662–9. 10.1016/S0268-0033(03)00090-1

68. Hansberger BL, Acocello S, Slater L V., Hart JM, Ambegaonkar JP. Peak lower extremity landing kinematics in dancers and nondancers. J Athl Train. 2018;53(4):379–85. 10.4085/1062-6050-465-16

69. Myer GD, Jayanthi N, Difiori JP, Faigenbaum AD, Kiefer AW, Logerstedt D, et al. Sport specialization, part I: Does early sports specialization increase negative outcomes and reduce the opportunity for success in young athletes? Sports Health. 2015;7(5):437–42. 10.1177/1941738115598747

70. McKay H, Tsang G, Heinonen A, MacKelvie K, Sanderson D, Khan KM. Ground reaction forces associated with an effective elementary school based jumping intervention. Br J Sports Med. 2005;39(1):10–4. 10.1136/bjsm.2003.008615

71. 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. 10.1016/j.jsams.2013.07.013

72. Bruce OL, Firminger CR, Wannop JW, Stefanyshyn DJ, Edwards WB. Effects of basketball court construction and shoe stiffness on countermovement jump landings. Footwear Sci. 2019;11(3):171–9. 10.1080/19424280.2019.1668867

73. Wei Q, Wang Z, Woo J, Liebenberg J, Park SK, Ryu J, et al. Kinetics and perception of basketball landing in various heights and footwear cushioning. PLoS One. 2018;13(8):1–9.

10.1371/journal.pone.0201758

74. Fu W, Liu Y, Zhang S. Effects of footwear on impact forces and soft tissue vibrations during drop jumps and unanticipated drop landings. Int J Sports Med. 2013;34(6):477–83. 10.1055/s-0032-1327696

75. Fu W, Fang Y, Gu Y, Huang L, Li L, Liu Y. Shoe cushioning reduces impact and muscle activation during landings from unexpected, but not self-initiated, drops. J Sci Med Sport. 2017;20(10):915–20. 10.1016/j.jsams.2017.03.009

76. Fukano M, Fukubayashi T. Changes in talocrural and subtalar joint kinematics of barefoot versus shod forefoot landing. J Foot Ankle Res. 2014;7(1):1–8. 10.1186/s13047-014-0042-9

77. Lindenberg KM, Lefever CR, Andreyo K, Vaughan R. The influence of heel height on muscle electromyography of the lower extremity during landing tasks in recreationally active females: A within subjects randomized trial. Int J Sports Phys Ther. 2019;14(6):866–76. 10.26603/ijspt20190866

78. Lindenberg KM, Carcia CR. The influence of heel height on vertical ground reaction force during landing tasks in recreationally active and athletic collegiate females. Int J Sports Phys Ther. 2013;8(1):1–8.

79. Hopper LS, Allen N, Wyon M, Alderson JA, Elliott BC, Ackland TR. Dance floor mechanical properties and dancer injuries in a touring professional ballet company. J Sci Med Sport. 2014;17(1):29–33. 10.1016/j.jsams.2013.04.013

80. Wyon M, Deighan M, Nevill A, Doherty M, Morrison S, Allen N, et al. The cardiorespiratory, anthropometrics, and performance characteristics of an international / national touring ballet company. J Strength Cond Res. 2007;21(2):56–61. 10.1519/R-19405.1

81. Jayalath JLR, de Noronha M, Weerakkody N, Bini R. Effects of fatigue on ankle biomechanics during jumps: A systematic review. J Electromyogr Kinesiol. 2018;42(June):81–91. 10.1016/j.jelekin.2018.06.012

82. Comyns TM, Brady CJ, Molloy J. Effect of attentional focus strategies on the biomechanical performance of the drop jump. J Strength Cond Res. 2019;33(3):626–32. 10.1519/jsc.0000000000003009

83. Harry JR, Lanier R, Nunley B, Blinch J. Focus of attention effects on lower extremity biomechanics during vertical jump landings. Hum Mov Sci. 2019;68:102521. 10.1016/j.humov.2019.102521

84. Louw Q, Grimmer K, Vaughan C. Knee movement patterns of injured and uninjured adolescent basketball players when landing from a jump: A case-control study. BMC Musculoskelet Disord. 2006;7:1–7. 10.1186/1471-2474-7-22

85. Goerger BM, Marshall SW, Beutler AI, Blackburn JT, Wilckens JH, Padua DA. Anterior

cruciate ligament injury alters preinjury lower extremity biomechanics in the injured and uninjured leg: The JUMP-ACL study. Br J Sports Med. 2015;49(3):188–95. 10.1136/bjsports-2013-092982

86. Smith M, Vicenzino B, Bahr R, Bandholm T, Cooke R, Mendonça L, et al. Establishing return to play criteria after acute lateral ankle sprain injuries: An international Delphi study. Vol. 22, Journal of Science and Medicine in Sport. 2019. p. S108–9. 10.1016/j.jsams.2019.08.147

Table 1 Jump kinetics and kinematics

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	Results	Measures	Results
Mertz & Docherty (38)	*n* = 30 uninjured (F = 23; M = 7) NP ballet dancers (Exp = 12.8 ± 4.0 y; Age = 19.6 ± 1.1 y; Height = 169.7 ± 8.7 cm; Mass = 55.2 ± 8.7 kg)	*Changement Entrechat Trois*	Force platform (200 Hz)	Peak landing vGRF; time to peak vGRF	↔ in vGRF (range: 2.19 ± 1.31 to 2.35 ± 0.39 BW) or time to peak vGRF (range: 0.12 ± 0.02 to 0.13 ± 0.02 s) across jump conditions.	-	-
Ravn et al. (35)	*n* = 3 P ballet dancers (Age = 21.3 ± 5.4 y; Height = 178.0 ± 6.5 cm; Mass = 69.1 ± 6.6 kg) *n* = 3 NDs (Age = 25.0 ± 1.4 y; Height = 187.3 ± 0.5 cm; Mass = 82.2 ± 5.8 kg)	*Entrechat Six*	2 force platforms (500 Hz); High-speed video camera (500 fps)	Peak and mean moment; peak power; and work	Peak ankle (3.1 ± 0.5 $Nm \cdot kg^{-1}$), knee (5.6 ± 1.1 $Nm \cdot kg^{-1}$), hip (-3.1 ± 0.4 $Nm \cdot kg^{-1}$) moment; average ankle (1.8 ± 0.3 $Nm \cdot kg^{-1}$), knee (3.1 ± 0.2 $Nm \cdot kg^{-1}$), and hip (-2.2 ± 0.3 $Nm \cdot kg^{-1}$) moment; peak ankle (17.6 ± 3.7 $W \cdot kg^{-1}$), knee (20.8 ± 9.5 $W \cdot kg^{-1}$), and hip (-4.5 ± 1.2 $W \cdot kg^{-1}$) power; and contribution of work done at the ankle (49.7 ± 10.0%), knee (64.7 ± 11.5%), and hip (-14.3 ± 1.9%).	-	-
McPherson, Schrader, & Docherty (52)	*n* = 21 F uninjured NP ballet dancers (Exp = 12.9 ± 2.4 y; Age = 19.3 ± 1.0 y; Height = 167.5 ± 4.4 cm; Mass = 52.7 ± 3.4 kg)	*Assemblé* and *Grand Jeté* under barefoot, ballet shoe, and pointe shoe conditions	Force platform; Video camera	Peak landing vGRF	↔ in vGRF across footwear conditions (range: 3.2 ± 0.4 to 3.8 ± 1.0 BW). vGRF ↑ during the *Grand Jeté* compared to the *Assemblé* (3.77 ± 0.91 vs. 3.30 ± 0.44 BW, respectively). ↔ in vGFR because of *pointe* shoe characteristics.	-	-
Volkerding & Ketcham (42)	*n* = 8 NP ballet dancers (Exp = 14.4 ± 3.1 y; Age = 20.5 ± 1.2 y; Height = 162.7 ± 7.3 cm; Mass = 56.9 ± 8.2 kg) *n* = 7 NDs (Age = 20.9 ± 0.4 y; Height = 166.4 ± 4.1 cm; Mass = 59.20 ± 5.2 kg)	Bilateral drop landings with and without vison from 20, 50, and 80 cm	Force platform (1000 Hz); High speed video camera (100 Hz)	Peak landing vGRF	↔ in vGRF between groups across heights (dancer 20cm: 2.7 ± 0.4; ND 20cm: 2.9 ± 0.9; dancer 50cm: 3.8 ± 0.9; ND 50cm: 3.6 ± 0.5; dancer 80cm: 4.4 ± 1.4; NDs 80cm: 4.3 ± 1.4 BW). ↑ vGRF was associated with higher drop heights across both groups. ↑ vGRF was associated with no vision during the 80 cm drop landing across both groups (dancer no-vison: 5.1 ± 2.2 vs ND no-vison: 4.5 ± 1.3 BW).	Peak joint angles	↑ ROM at the knee (dancer 20 cm: 59.2 ± 13.5°; ND 20 cm: 60.4 ± 14.6°; dancer 50 cm: 67.7 ± 18.1°; ND 50 cm: 69.6 ± 18.1°; dancer 80 cm: 79.8 ± 24.2°; ND 80 cm: 73.7 ± 16.5°) followed by the ankle (dancer 20 cm: 60.5 ± 18.4°; ND 20 cm: 56.2 ± 11.9°; dancer 50 cm: 59.9 ± 23.3°; ND 50 cm: 59.0 ± 19.8°; dancer 80 cm: 59.8 ± 17.0°; ND 80 cm: 59.7 ± 11.9°) and the hip (dancer 20 cm: 32.4 ± 23.4°; ND 20 cm: 25.4 ± 20.8°; dancer 50 cm: 42.2 ± 16.3°; ND 50 cm: 44.2 ± 21.4°; dancer 80 cm: 62.8 ± 38.8°; ND 80 cm: 57.8 ± 31.6°). ↔ in ankle ROM across drop heights. ↑ knee and hip ROM with higher drop heights. ↑ ROM during the 80 cm drop landing without vision in dancers compared to NDs.

Table 1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	Results	Measures	Results
Imura & Iino (54)	*n* = 12 F uninjured P ballet dancers (Age = 30.0 ± 1.0 y; Height = 159.0 ± 2.0 cm; Mass = 46.5 ± 1.3 kg)	*Sauté* in 1st position; CMJ	Two force platforms (1000 Hz); 8 camera 3D motion analysis system (250 Hz)	Peak joint moment, and work; sum of positive work	↔ in hip EXT torque (TO: 0.67 ± 0.23; parallel: 0.60 ± 0.12 $Nm·(BM·Ht)^{-1}$, ankle PF torque (TO: 0.80 ± 0.09; parallel: 0.78 ± 0.10 $Nm·(BM·Ht)^{-1}$, the sagittal hip moment (TO: 1.36 ± 0.34 vs. parallel: 1.44 ± 0.31 $Nm·(BM·Ht)^{-1}$, hip, knee, or ankle joint work, the sum of work by the frontal hip moment (TO: 0.08 ± 0.05; parallel: 0.04 ± 0.02 $J·(BM·Ht)^{-1}$, or the sum of positive work (TO: 2.56 ± 0.24; parallel: 2.53 ± 0.30 $J·(BM·Ht)^{-1}$. Hip ABD torque (TO: 0.22 ± 0.08; parallel: 0.34 ± 0.11 $Nm·(BM·Ht)^{-1}$, knee EXT torque (TO: 0.84 ± 0.12; parallel: 0.89 ± 0.10 $Nm·(BM·Ht)^{-1}$, and the sum of work by the sagittal hip moment ↑ in parallel compared to TO (TO: 0.28 ± 0.08; parallel: 0.33 ± 0.09 $J·(BM·Ht)^{-1}$. Hip ER torque ↑ in TO compared to parallel (TO: 0.08 ± 0.05; parallel: 0.03 ± 0.01 $Nm·(BM·Ht)^{-1}$).	Peak joint angles and excursions	Mean AP rotation (TO: 18.2 ± 3.8°; parallel: 20.09 ± 4.4°) and total excursion of the lower trunk (TO: 15.1 ± 2.9°; parallel: 17.1 ± 4.1°), and peak hip FLEX angle (TO: 52.7 ± 6.1°; parallel: 59.0 ± 6.2°) ↑ in parallel compared to TO. Hip ABD (TO: 24.3 ± 5.6°; parallel 4.4 ± 1.5°), thigh ER (34.1 ± 8.0°; parallel: 3.6 ± 1.4°) and foot ER angle (TO: 59.4 ± 8.3°; parallel: 16.4 ± 6.3°) was ↑ in TO compared to parallel. ↔ in knee FLEX angle (TO: 89.9 ± 1.55°; parallel: 90.1 ± 1.4°) or ankle DF angle (TO: 82.5 ± 3.1°; parallel: 82.8 ± 3.1°) between TO and parallel.
Picon et al. (32)	*n* = 13 NP ballet dancers (Exp = 15.2 ± 3.9 y; Age = 21.1 ± 3.1 y; Height = 162 ± 1.0 cm; Mass = 51.8 ± 6.0 kg) *n* = 8 NP ballet dancers (Exp = 3.2 ± 1.6 y; Age = 10.6 ± 1.7 y; Height = 147 ± 0.0 cm; Mass = 44.8 ± 10.1 kg) *n* = 7 NP dancers (Exp = 13.5 ± 6.3 y; Age = 21.3 ± 3.2 y; Height = 161 ± 5.0 cm; Mass = 53.8 ± 4.9 kg)	*Sauté* in 1st position	Force platform (1000 Hz); 6 infrared cameras (100 Hz)	-	-	Peak ER angle and excursion	Peak hip ER angles ↑ in dancers from mixed training methods compared to experienced and inexperienced ballet dancers (31.4 ± 3.9° vs. 25.5 ± 4.8° vs. 22.2 ± 6.5°, respectively). ↔ in hip (range: 12.6 ± 2.2 to 13.4 ± 2.3), knee (range: 19.1 ± 4.6 to 19.4 ± 3.8°), or ankle (range: 24.4 ± 7.0 to 28.8 ± 8.1°) excursions, or ER angles at the knee (range: 15.5 ± 4.7 to 19.7 ± 6.4°) and ankle (2.1 ± 5.0 to 6.8 ± 6.2°) between groups.
Kirkendall & Street (40)	*n* = 12 M P ballet dancers (Age = 25.4 ± 4.9 y; Mass = 69.5 ± 8.6 kg) 6 different athletic teams	Repeated CMJ to 90° knee flexion Bosco et al. (81)	Jump mat	Mean power	Professional ballet dancers (18.1 ± 2.2 $W·kg^{-1}$) demonstrated ↓ power compared to professional indoor soccer athletes (21.5 ± 4.2 $W·kg^{-1}$), amateur bobsled athletes (21.9 ± 7.5 $W·kg^{-1}$), and college basketball athletes (22.2 ± 5.8 $W·kg^{-1}$).	-	-

Table 1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	Results	Measures	Results
Hendry et al. (36)	*n* = 15 F uninjured NP ballet dancers (Age = 11.9 ± 1.0 y; Height = 156.3 ± 8.3 cm; Mass = 42.5 ± 8.3 kg) *n* = 17 F uninjured non-dancers (Age = 10.9 ± 0.9 y; Height = 152.7 ± 7.5 cm; Mass = 42.0 ± 9.5 kg)	Single leg drop landing from 30 cm	Force platform (2000 Hz); 18 camera 3D motion analysis system (250 Hz)	Peak landing vGRF; landing phase duration	↔ in vGRF (dancers: 5.0 ± 0.9 BW; ND: 5.4 ± 0.9 BW) or landing phase duration (dancers: 0.4 ± 0.2 s; ND: 0.4 ± 0.2 s) was observed between non-dancers and dancers.	Peak joint angles and excursion	Dancers demonstrated ↑ sagittal ankle (dancers: 54.3 ± 6.6°; ND: 44.5 ± 5.3°), knee (dancers: 57.9 ± 7.4°; ND: 46.9 ± 8.9°), and hip (dancers: 29.1 ± 7.4°; ND: 21.4 ± 6.8°) joint excursions; ↑ transverse knee joint excursions (dancers: 20.1 ± 5.6°; ND: 14.0 ± 9.0°); ↑ ankle eversion (dancers: 15.5 ± 4.3°; ND: 9.2 ± 3.2°); ↑ knee EXT (dancers: 0.5 ± 2.9°; ND: 5.2 ± 4.0°); knee ER (dancers: 8.0 ± 4.2°; ND: 2.1 ± 6.0°); and ↑ hip EXT (dancers: 13.6 ± 5.1°; ND: 19.5 ± 5.1°) angles compared to non-dancers. ↔ across all other joint excursion and angles.
Chockley (34)	*n* = 7 NP ballet dancers	*Sauté* in 1st landing on a flat foot and en pointe	Force platform	Peak landing vGFR; landing phase durations	vGRF was greater when landing on a flat foot compared to en pointe (736 ± 96 N vs. 531 ± 82 N).	-	-
Miller et al. (45)	*n* = 1 M P ballet dancer (Exp = 16 ± 0.0 y; Mass = 68.0 ± 0.0 kg)	*Grand Jeté* under barefoot, and 12 ballet shoe conditions	Force platform; High speed video camera (200 Hz)	Peak landing vGRF	No statistical tests were conducted, and no raw data presented.	-	-
Hackney et al. (41,59)	*n* = 7 F uninjured NP ballet dancers (Age = 22.7 ± 2.6 y)	*Échappé Sauté* under stiff and sprung floor conditions	Insole foot pressure system (50 Hz); High-speed video camera (210 Hz)	Lower extremity stiffness	↑ lower extremity stiffness values in the sprung floor compared to the stiff floor (sprung: 9302 ± 3937 $kN \cdot m^{-1}$; stiff: 6823 ± 2568 $kN \cdot m^{-1}$).	-	-
Hackney et al. (55)	*n* = 13 F uninjured NP ballet dancers (Age = 20.9 9 ± 2.9 y)	*Échappé Sauté* under stiff and sprung floor conditions	Ariel Performance Analysis System; 2 2D video cameras (60 fps)	-	-	Peak joint FLEX; Peak negative velocity	↓ peak knee angles (sprung: 55.2 ± 11.5°; stiff: 57.8 ± 9.6°) and ankle velocities were observed during the sprung floor compared to the stiff floor (sprung: 492 ± 50$° \cdot s^{-1}$; stiff: 513 ± 47$° \cdot s^{-1}$). ↔ in ankle and hip peak angles or velocities was observed across floor conditions.

Table 1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	Results	Measures	Results
Harwood et al. (33)	*n* = 13 F uninjured NP ballet dancers (Age = 11.8 ± 1.1 y; Height = 160.0 ± 8.0 cm; Mass = 41.1 ± 7.4 kg) *n* = 17 F uninjured ND (Age = 10.9 ± 0.8 y; Height = 150.0 ± 7.2 cm; Mass = 42.2 ± 9.6 kg)	Unilateral vertical hop (hop); Unilateral horizontal hop and stick with 10-meter run in (stop jump)	Force platform (2000 Hz); 18 camera 3D motional analysis system (250 Hz)	Peak landing vGRF; time to peak landing vGRF; peak joint moment	↔ in vGRF were observed between dancers and ND across both jump conditions. ↔ in time to peak vGRF between dancers and ND during the hop (dancers: 35 ± 0; ND: 37 ± 0% of total landing time). Dancers demonstrated ↑ hip EXT moments (dancers: -3.16 ± 1.13; ND: -2.05 ± 0.82 $Nm·kg^{-1}$) and slower times to peak landing vGRF (dancers: 43 ± 0; ND: 28 ± 0% of total landing time) during the stop jump compared to ND. ↔ in ankle or knee moments were observed between dancers and ND.	Peak joint angles and excursion; approach velocity	↑ frontal knee excursions during the h dancers compared to ND (13.4 ± 3.4° 4.1°, respectively). ↑ sagittal hip excu dancers compared to ND during the s (13.4 ± 4.1° vs. 9.7 ± 3.3°, respectivel ankle PF (dancers hop: 33.4 ± 9.0°; N 17.3 ± 8.5°; dancers stop jump: 31.9 : ND stop jump: 22.3 ± 9.7°), sagittal ar excursions (dancers hop: 58.6 ± 6.8°; 36.6 ± 9.5°; dancers stop jump: 45.5 : ND stop jump: 30.7 ± 10.8°), knee EX landing (dancers hop: 2.1 ± 4.5°; ND ± 7.4°; dancers stop jump: 2.9 ± 5.1°; jump: 8.1 ± 5.2°), sagittal knee excurs (dancers hop: 51.8 ± 12.0°; ND hop: 3 13.6°; dancers stop jump: 48.3 ± 9.4° jump: 38.5 ± 6.6°), hip EXT prior to la (dancers hop: 12.0 ± 5.9°; ND stop ju ± 9.4°; dancers stop jump: 20.6 ± 7.2° jump: 34.7 ± 8.7°), and ↓ hip FLEX ar (dancers: 34.1 ± 5.8°; ND: 44.4 ± 8.6° dancers compared to ND. ↔ in horizo approach velocity during the stop jum
Hackney et al. (39)	*n* = 13 F uninjured NP ballet dancers (Age = 21.3 ± 2.1 y)	*Grand Jeté* under stiff and sprung floor conditions	Insole foot pressure system (100 Hz); 2D video camera (50 Hz)	Lower extremity stiffness	Lower extremity stiffness was greater under sprung floor condition compared to stiff floor (15591 ± 16442 vs. 9423 ± 6295 $N·m^{-1}$, respectively). No alpha level provided; statistical analysis unclear.	-	-
Walter, Docherty, & Schrader (60)	*n* = 18 F uninjured NP ballet dancers (Exp = 14.2 ± 2.9 y; Age = 19.9 ± 1.2 y; Height = 169.1 ± 6.4 cm; Mass = 55.4 ± 5.4 kg)	*Assemblé* under flat shoe and pointe shoe conditions	Force platform; Video camera	Peak landing vGRF	↑ vGRF in flat shoes compared to pointe shoes (1743 ± 253 vs. 1613 ± 262 N).	-	-
Couillandre, Lewton-Brain, & Portero (43)	*n* = 7 F uninjured P ballet dancers (Age = 31.0 ± 9.0 y; Height = 169.0 ± 4.0 cm; Mass = 51.0 ± 3.0 kg)	*Sauté* in 1^{st} before and after mental imagery intervention	2D accelerometer; Electrogoniometer	-	-	Peak FLEX angle; peak impact acc; time to peak impact acc	↔ in peak knee flexion angle, acc, or peak acc.

Table 1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	Results	Measures	Results
Fong Yan et al. (57)	*n* = 16 F uninjured NP ballet dancers (Age = 25.0 ± 5.9 y; Mass = 55.9 ± 7.4 kg)	*Sauté* in 2^{nd} position across barefoot and a high heeled chorus shoe condition	14 camera 3D motion analysis system	-	-	Peak joint angles and excursion	↑ sagittal knee (chorus: 69.1 ± 4.9; barefoot: 66.2 ± 5.8°) and ankle (chorus: 62.4 ± 4.1; barefoot: 53.6 ± 10.8°) ROM, ↓ frontal ankle ROM (chorus: 16.5 ± 5.5; barefoot: 19.9 ± 4.3°), and ↓ sagittal midfoot (chorus: 12.8 ± 2.8; barefoot: 38.6 ± 8.8°), frontal midfoot (chorus: 4.2 ± 1.4; barefoot: 10.0 ± 4.2°), an transverse midfoot (chorus: 5.0 ± 2.1; barefoot: 13.3 ± 5.0°) ROM observed in chor shoe compared to barefoot. ↔ in sagittal hip ROM between chorus shoe and barefoot (chorus: 29.7 ± 5.6; barefoot: 29.6 ± 6.8°). Chorus shoes demonstrated smaller midfoot and MPJ peak joint angles.
Fong Yan et al. (44)	*n* = 16 F uninjured NP ballet dancers (Age = 25.0 ± 5.9 y; Mass = 56.0 ± 7.4 kg)	*Sauté* in 2^{nd} position under barefoot and a high heeled shoe condition	2 force platforms; 3D motion analysis system	Joint stiffness	↓ knee stiffness in chorus shoe compared to barefoot condition (15.3 ± 7.6 vs. 34.8 ± 14.2 Nmm·deg^{-1}). ↔ in hip (chorus: 60.6 ± 183.7; barefoot: 30.4 ± 24.5 Nmm·deg^{-1}), ankle (chorus: 37.6 ± 9.4; barefoot: 40.4 ± 12.3 Nmm·deg^{-1}), or midfoot (chorus: -6.8 ± 22.9; barefoot: 5.3 ± 29.9 Nmm·deg^{-1}) joint stiffness between chorus shoe and barefoot conditions.	-	-
Hendry et al. (37)	*n* = 18 uninjured NP ballet dancers (Age = 13.2 ± 1.0 y; Height = 160.0 ± 10.0 cm; Mass = 45.4 ± 7.4 kg)	*Sauté* in 1^{st} and 2^{nd} position and *Temp Leve* under no tape, kinesio tape, and Mulligan's tape conditions	Force platform (1000 Hz); 14 camera 3D motion analysis system (250 Hz)	Peak joint Fz	↑ posterior knee Fz (no tape: 307 ± 130; tape: 241 ± 121 N), and posterior (no tape: 621 ± 268; tape 481 ± 218 N), medial (no tape: 202 ± 71; tape: 164 ± 79 N), and lateral (no tape: 292 ± 96; tape: 240 ± 105 N) hip Fz with no tape compared to Mulligan's taping when landing in 1^{st}. ↔ in knee and hip Fz when jumping in 2^{nd}. ↓ posterior hip Fz with Mulligan's taping compared to Kinesiotape during Temp Levé.	Peak FLEX angles	↔ in knee or hip FLEX across each taping condition during landing in 1^{st} (knee FLEX range: 56.6 ± 18.2° to 58.0 ± 18.8°; hip FLE range: 39.7 ± 12.4° to 40.9 ± 12.4°), 2^{nd} (kne FLEX range: 61.1 ± 19.2° to 61.5 ± 18.2°; hi FLEX range: 41.6 ± 12.5° to 42.3 ± 14.2°), o temp leve (knee FLEX range: 56.6 ± 18.2° t 58.0 ± 18.8°; hip FLEX range: 39.0 ± 11.5° t 41.9 ± 12.3°).
Escobar Álvarez et al. (46)	*n* = 46 F P ballet dancers (Age = 18.9 ± 1.1 y; Height = 163.7 ± 8.4 cm; Mass = 54.8 ± 6.1 kg)	CMJ at 0, 10, 20, 30, 40, 50, and 70% of BM pre-post intervention	Application on smartphone device (240 fps)	Peak Fz; Peak power; F-V$_{IMB}$	↑ Fz post intervention in EG (pre: 24.1 ± 2.2; post: 29.9 ± 2.8 N·kg^{-1}). ↑ Fz in EG compared to the CG post intervention (EG: 29.9 ± 2.8; CG: 23 ± 2.4 N·kg^{-1}). ↓ F-V$_{IMB}$ post intervention in EG (pre: 43.8 ± 15.3; post: 24.9 ± 8.7%).	Peak velocity	↓ velocity post intervention in EG (pre: 4.0 ± 0.6; post: 3.2 ± 0.5 m·s^{-1}). ↓ velocity in EG compared to the CG post intervention (CG: 4 ± 0.7; EG: 3.2 ± 0.5 m·s^{-1}).

Table 1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	Results	Measures	Results
Almonroeder et al. (53)	*n* = 15 F uninjured P and NP ballet dancers (Age = 18.1 ± 4.5 y; Height = 165.0 ± 10.0 cm; Mass = 53.9 ± 7.3 kg)	*Changement de Pied* until self-determined exhaustion	2 force platforms (600 Hz); Tri-axial accelerometer (500 Hz)	Peak landing vGRF; Loading rate	↑ peak landing vGFR and LR at 25 (vGRF: 3.8 ± 0.6 BW; LR: 53.3 ± 16.8 BW·s^{-1}), 50 (vGRF: 3.9 ± 0.5 BW; LR: 55.5 ± 13.9 BW·s^{-1}), 75 (vGRF: 3.9 ± 0.5 BW; LR: 55.1 ± 12.4 BW·s^{-1}), and 100% (vGRF: 3.9 ± 0.5 BW; LR: 55.6 ± 12.9 BW·s^{-1}) of test compared to baseline (vGRF: 3.6 ± 0.7 BW; LR: 47.7 ± 15.3 BW·s^{-1}).	Peak impact acc	↑ peak impact acc at 25% (4.6 ± 0.6 g), 5 (4.7 ± 0.5 g), 75% (4.7 ± 0.4 g), and 100% ± 0.4 g) of test compared to baseline (4.2 g). +ve relationships were observed betw peak impact acc and peak vGRF (range: 0.95 to 0.98) and LR (range: r = 0.80 to 0 across all time points.
Peng et al. (56)	*n* = 11 F injured (PFP) NP ballet dancers (Age = 18.3 ± 0.5 y; Height = 161.9 ± 3.3 cm; Mass = 51.6 ± 4.7 kg) *n* = 14 F uninjured NP ballet dancers (Age = 18.2 ± 0.4 y; Height = 159.5 ± 3.8 cm; Mass = 50.2 ± 4.6 kg)	*Échappé* to a tempo of 75 bpm under non-fatigued and fatigued condition	2 force platforms (2000 Hz); 11 infrared cameras (200 Hz)	Peak landing vGRF; Peak joint stiffness, power, angular impulse, moment; and PFJS	↑ landing vGRF (PFP: 1.50 ± 0.15; uninjured: 1.35 ± 0.11 BW), knee power (PFP: 8.95 ± 2.92; uninjured: 7.37 ± 1.50 W·kg^{-1}) and PFJS (PFP: 0.14 ± 0.02; uninjured: 0.13 ± 0.02 MPa·kg^{-1}) in PFP group compared to uninjured group. ↑ hip stiffness and hip ER impulse under fatigue compared to no-fatigue. ↓ landing peak knee EXT moment (no fatigue: -1.72 ± 0.58; fatigue: -1.56 ± 0.62 Nm·kg^{-1}), knee ER moment (no fatigue: 0.36 ± 0.15; fatigue: 0.30 ± 0.23 Nm·kg^{-1}), ankle power (PFP no fatigue: 9.12 ± 0.97; PFP fatigue: 6.89 ± 2.12; uninjured no fatigue: 8.58 ± 1.35; uninjured fatigue: 7.28 ± 1.29 W·kg^{-1}) and PFJS (PFP fatigue: 0.13 ± 0.02; uninjured fatigue: 0.11 ± 0.02 MPa·kg^{-1}) under fatigue compared to no-fatigue. ↔ landing vGRF, knee and ankle stiffness, or hip and knee power absorption across fatigue conditions.	Peak joint angles	At initial ground contact, ↓ ankle PF (no fatigue: -50.4 ± 11.3°; fatigue: -46.4 ± 19. angle under fatigue compared to no fatig Ankle DF (no fatigue: 60.1 ± 9.6°; fatigue ± 14.2°) excursion during landing under f compared to no-fatigue. ↔ in any other excursion or joint angle at initial contact c position of lowest COM across all joints, i and fatigue conditions.
Lee et al. (58)	*n* = 11 F NP injured (previous LAS) ballet dancers (Age = 19.7 ± 2.4 y; Height = 162.2 ± 3.2 cm; Mass = 53.9 ± 4.9 kg) *n* = 11 F uninjured NP ballet dancers (Age = 18.8 ± 3.1 y; Height = 160.2 ± 5.0 cm; Mass = 51.0 ± 5.6 kg)	*Sissonne Fermée*	Force Platform (1000 Hz); 8 high speed optical cameras (100 Hz)	Peak landing vGRF; Loading rate	↔ in vGRF between previously injured dancers and uninjured dancers (1.6 ± 0.2 vs. 1.7 ± 0.3 BW, respectively). Previously injured dancers had ↓ LR compared to uninjured dancers (9.5 ± 1.9 vs. 11.0 ± 3.4 BW·s^{-1}, respectively).	Peak joint angles	↑ ankle eversion (injured: 11.9 ± 7.6°; uninjured: 8.1 ± 2.9°) and ↓ hindfoot-to-tib eversion (injured: 0.6 ± 17.1°; uninjured: ± 13.7°) in previously injured dancers compared to uninjured dancers. ↔ acros other joint angles.

Table 1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	Results	Measures	Results
Arnwine & Powell (47)	*n* = 7 uninjured ballet dancers (P = 3; NP =4; Age 23.4 ± 4.7 y; Height 165.0 ± 5.3 cm; Mass 61.0 ± 5.6 kg) n = 7 uninjured M ballet dancers (P = 4; NP =3; Age 27.4 ± 4.4 y; Height 173.4 ± 9.7 cm; Mass 69.7 ± 8.9 kg)	*Grand Jeté* *Sauté*	2 force platforms (1200 Hz)	Peak landing vGRF; Time to peak vGRF; Vertical impulse; Loading rate	↑ peak landing vGRF in females compared to males during *Grand Jeté* (3.8 ± 0.1 vs. 2.8 ± 0.8 BW, respectively) but not *Sauté* (1.5 ± 0.3 vs. 1.6 ± 0.4 BW, respectively). ↓ time to peak vGFR in females compared to males during the *Grand Jeté* (0.05 ± 0.00 vs. 0.09 ± 0.05 s, respectively) but not the *Sauté* (0.10 ± 0.01 vs. 0.10 ± 0.04, respectively). ↑ vertical impulse in females compared to males during *Grand Jeté* (0.56 ± 0.03 vs. 0.49 ± 0.09 $N \cdot kg \cdot s^{-1}$, respectively) but not *Sauté* (0.29 ± 0.03 vs. 0.29 ± 0.06 $N \cdot kg \cdot s^{-1}$, respectively). ↑ loading rate in females compared to males during *Grand Jeté* (78.2 ± 9.3 vs. 49.9 ± 15.6 $BW \cdot s^{-1}$, respectively) but not *Sauté* (16.1 ± 4.7 vs. 18.5 ± 9.0 $BW \cdot s^{-1}$, respectively).	-	-
Escobar Álvarez et al. (48)	*n* = 87 F P ballet dancers (Age: 18.9 ± 1.3 y; Height: 164.4 ± 8.2 cm; Mass: 56.3 ± 5.9 kg)	CMJ at 0, 10, 20, 30, 40, 50, and 70% of BM	Application on smartphone device (240 fps)	Peak Fz; Peak power; $F\text{-}V_{IMB}$	Peak Fz was 25.2 ± 2.0 $N \cdot kg^{-1}$, peak power was 23.0 ± 4.1 $W \cdot kg^{-1}$, and $F\text{-}V_{IMB}$ was 45.6 ± 13.5%. Soloists (27.3 ± 4.6 $W \cdot kg^{-1}$) demonstrated ↑ peak power compared to Second Soloists (23.5 ± 3.0 $W \cdot kg^{-1}$). Soloists and Second Soloists demonstrated ↑ peak power compared to the *Corps de Ballet* (20.9 ± 3.2 $W \cdot kg^{-1}$).	Peak velocity	Peak velocity was 3.7 ± 0.8 $m \cdot s^{-1}$. Soloists (4.2 ± 0.8 $m \cdot s^{-1}$) and Second Soloists (3.8 ± 0.7 $m \cdot s^{-1}$) demonstrated ↑ peak velocity compared to the *Corps de Ballet* (3.4 ± 0.7 $m \cdot s^{-1}$).
Perry et al. (49)	*n* = 15 uninjured F NP ballet dancers (Exp = 13.9 ± 5.0 y; Age: 20.7 ± 2.7 y; Height: 160.0 ± 10.0 cm; Mass: 56.4 ± 4.0 kg)	*Saut de Chat* *Temp Levé*	2 force plates (1000 Hz);10-camera 3D motion capture system (250 Hz)	Peak vGRF; Peak ankle joint moment; Mean RFD; Peak ankle power	↑ peak vGRF (23.2 ± 2.7 vs. 21.2 ± 2.3 $N \cdot kg^{-1}$, respectively), peak ankle joint moment (3.03 ± 0.40 vs. 2.61 ± 0.38 $Nm \cdot kg^{-1}$, respectively), mean RFD (103.3 ± 35.6 vs. 74.4 ± 17.8 $N \cdot s \cdot kg^{-1}$, respectively), and peak ankle power (20.7 ± 4.7 vs. 15.6 ± 3.5 $W \cdot kg^{-1}$) was observed during the *Saut de Chat* compared to the *Temp Levé*.	-	-

Table 1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	Results	Measures	Results
Gorwa et al. (50)	*n* = 1 F P ballet dancer (Age = 27.0 y; Height 152.0 cm; Mass 42.0 kg)	*Grand Jeté* *Entrelacé* *Ballonné*	Force platform; 4 digital cameras (200 Hz); Ariel Performance Analysis System	Peak landing vGRF; Loading rate; Peak ankle, knee, and hip joint moments	No statistical comparisons between positions were made. Peak landing vGRF and loading rate during the *Grand Jeté* (9.6 ± 1.4 BW and 222.7 ± 39.9 BW·s^{-1}, respectively), *Entrelacé* (7.4 ± 0.3 BW and 114.9 ± 4.3 BW·s^{-1}, respectively) and *Ballonné* (7.5 ± 0.1 BW and 123.1 ± 4.7 BW·s^{-1}, respectively). Peak joint moments at the ankle, knee, and hip for the *Grand Jeté* (2.3 ± 0.3 vs. 4.1 ± 1.0 vs. 8.8 ± 1.2 Nm·kg^{-1}, respectively), *Entrelacé* (2.9 ± 0.3 vs. 10.8 ± 2.1 vs. 15.2 ± 3.7 Nm·kg^{-1}, respectively), and *Ballonné* (3.6 ± 0.1 vs. 15.7 ± 0.5 vs. 19.9 ± 0.6 Nm·kg^{-1}, respectively).	Peak joint angles and excursions	Peak ankle, knee, and hip joint angles during the *Grand Jeté* (-5.7 ± 2.5 vs. 15.0 ± 2.9 vs. 59.7 ± 4.9°, respectively), *Entrelacé* (16.0 ± 2.8 vs. 18.0 ± 0.8 vs. 57.3 ± 6.6°, respectively), and *Ballonné* (11.3 ± 0.5 vs. 31.3 ± 0.5 vs. 23.3 ± 1.2°, respectively). Ankle, knee, and hip excursions during the *Grand Jeté* (41.7 ± 2.1 vs. 11.3 ± 2.5 vs. 15.3 ± 4.0°), *Entrelacé* (58.7 ± 3.1 vs. 15.3 ± 1.7 vs. 16.3 ± 3.3°), and *Ballonné* (49.3 ± 1.7 vs. 24.7 ± 3.4 vs. 7.3 ± 1.2°).
Dworak et al. (51)	*n* = 1 M P ballet dancer (Mass = 56.5) *n* = 1 P ballet dancer (Mass = 59.5)	*Grand pas de Chat* *Grand Jeté* *Entrelacé* *Double Tour* *Jeté en Tournant* *Grand pas Assemblé* *Saut de Basque* *Pas Jeté* *Entrechat*	1 force platform (1000 Hz) and two video cameras	Peak landing vGRF; Loading rate	No statistical comparisons between positions were made. Peak landing vGRF ranged between 5.3 - 9.4 BW, with the highest values observed during the *Grand pas de Chat* and the *Grand Jeté*. Loading rate ranged between 26.2 - 128.5 BW·s^{-1}, with the highest values observed during the *Grand pas de Chat*.	-	-

Raw data were rounded to one decimal place and units were adjusted to ensure consistency in reporting (e.g., weight to mass; meters to cm). *F* female, *NP* non-professional, *ND* non-dancer, *TO* turn-out, *vGRF* vertical ground reaction force, *FLEX* flexion, *M* male, *Exp* experience, *P* professional, *CMJ* countermovement jump, ↔ no statistical change/difference, ↑ statistical increase, ↓ statistical decrease, *BW* bodyweight, *ROM* range of motion, *BM* body mass, *Ht* height, *J* joules, *EXT* extension, *deg* degree, *PF* plantarflexion, *ABD* abduction, *ER* external rotation, *AP* anteroposterior, *ML* mediolateral, *DF* dorsiflexion, *MPJ* metatarsophalangeal joint, *Fz* force, *Max* maximum, $F\text{-}V_{IMB}$ force-velocity imbalance, *EG* experimental group, *CG* control group, *acc* acceleration, *+ve* positive, *PFP* patellofemoral pain, *PFJS* patellofemoral joint stress, *LAS* lateral ankle sprain

Table 2 Jump phases

Study	Take-Off		Landing	
	Kinetics	Kinematics	Kinetics	Kinematics
Ravn et al. (35)	*			
Perry et al. (49)	*			
Kirkendall & Street (40)	*			
Escobar Álvarez et al. (48)	*	*		
Escobar Álvarez et al. (46)	*	*		
Imura & Iino (54)	*	*		
Harwood et al. (33)		*	*	*
Arnwine & Powell (47)			*	
Dworak et al. (51)			*	
Chockley (34)			*	
Miller et al. (45)			*	
Hackney et al. (59)			*	
Hackney et al. (39)			*	
Hackney et al. (41)			*	
Walter, Docherty, & Schrader (60)			*	
Fong Yan et al. (44)			*	
Mertz & Docherty (38)			*	
McPherson, Schrader, & Docherty (52)			*	
Volkerding & Ketcham (42)			*	*
Hendry et al. (37)			*	*
Almonroeder et al. (53)			*	*
Peng et al. (56)			*	*
Lee et al. (58)			*	*
Hendry et al. (36)			*	*
Gorwa et al. (50)			*	*
Picon et al. (32)				*
Hackney et al. (55)				*
Couillandre, Lewton-Brain, and Portero (43)				*
Fong Yan et al. (57)				*

Table 3 Organizational themes

Study	Environment & Equipment	Activity Type	Demographics	Physical Characteristics	Injury Status	Skill Acquisition & Motor Control
Miller et al. (45)	*					
Hackney et al. (59)	*					
Hackney et al. (55)	*					
Hackney et al. (39)	*					
Hackney et al. (41)	*					
Walter, Docherty, & Schrader (60)	*					
Fong Yan et al. (57)	*					
Fong Yan et al. (44)	*					
Hendry et al. (37)	*					
McPherson, Schrader, & Docherty (52)	*	*				
Chockley (34)		*				
Perry et al. (49)		*				
Imura & Lino (54)		*				
Gorwa et al. (50)		*				
Dworak et al. (51)		*				
Mertz & Docherty (38)		*				
Ravn et al. (35)		*	*			
Volkerding & Ketcham (42)		*	*			
Arnwine & Powell (47)		*	*			
Picon et al. (32)			*			
Kirkendall & Street (40)			*			
Hendry et al. (36)			*			
Harwood et al. (33)			*			
Escobar Álvarez et al. (48)			*			
Escobar Álvarez et al. (46)				*		
Almonroeder et al. (53)				*		
Peng et al. (56)				*	*	
Lee et al. (58)					*	
Couillandre, Lewton-Brain, & Portero (43)						*

Activity Type included studies that manipulated variables such as limb position, contraction type, technique, or drop height. *Demographics* included studies that investigated factors such as age, sex, training history, or dance genre. *Environment and Equipment* included studies that investigated factors such as floor surface properties, floor inclination, shoe condition, or taping. *Physical Characteristics* included studies that investigated factors such as strength, training interventions, and fatigue resistance. *Skill Acquisition and Motor Control* included studies that investigated variables such as focus of attention, self-talk, and imagery. *Injury Status* included studies that investigated factors such as current or previous injury.

Table 4 Appraisal scores using the AXIS tool

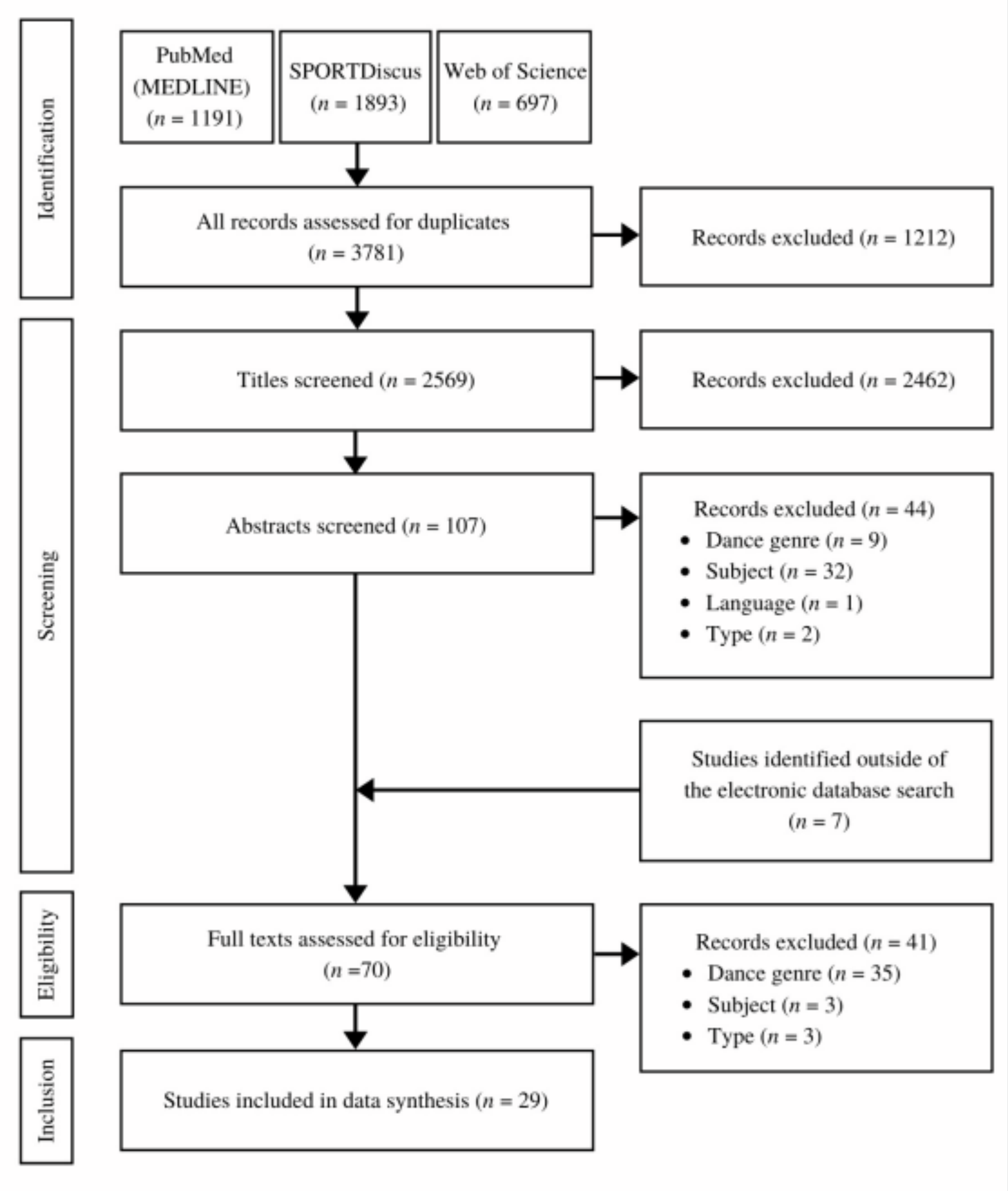
Study	Intro.	Methods										Results					Discussion		Other		Total / 1
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Chockley (34)	0	0	0	0	0	1	-	0	0	0	0	0	-	-	-	0	0	0	0	1	2
Miller et al. (45)	1	1	0	0	0	1	-	0	0	0	0	0	-	-	-	0	0	0	0	0	3
Dworak et al. (51)	1	0	0	0	0	1	-	0	1	0	0	0	-	-	-	0	0	0	1	1	5
Couillandre, Lewton-Brain, & Portero (43)	0	0	0	1	0	1	-	0	0	1	0	0	-	-	-	1	0	1	0	1	6
Hackney et al. (59)	1	1	1	0	0	1	-	1	0	0	0	0	-	-	-	1	0	0	0	1	7
Gorwa et al. (50)	1	1	0	1	0	1	-	1	0	0	0	1	-	-	-	1	0	0	1	0	8
Mertz & Docherty (38)	0	0	0	0	1	1	-	0	0	1	0	1	-	-	-	1	1	1	0	1	8
Hackney et al. (55)	1	1	0	0	1	1	-	1	0	0	1	0	-	-	-	0	0	1	0	1	8
Hackney et al. (39)	1	1	0	0	1	1	-	1	0	0	1	0	-	-	-	1	0	1	0	1	9
Hackney et al. (41)	1	1	0	1	0	1	-	1	0	0	1	1	-	-	-	1	1	0	0	0	9
Ravn et al. (35)	1	1	0	0	1	1	-	1	1	1	0	1	-	-	-	1	1	0	0	0	10
Walter, Docherty, & Schrader (60)	1	1	0	1	1	1	-	1	1	1	0	0	-	-	-	1	0	0	0	1	10
Picon et al. (32)	1	1	1	0	1	1	-	1	1	1	0	0	-	-	-	0	0	1	0	1	10
Arnwine & Powell (47)	1	1	0	1	1	1	-	1	1	0	0	1	-	-	-	1	0	1	0	1	11
Kirkendall & Street (40)	1	1	0	0	1	1	-	1	1	1	1	1	-	-	-	1	1	0	0	0	11
Fong Yan et al. (57)	1	1	0	0	1	1	-	1	1	1	1	1	-	-	-	0	0	1	0	1	11
Fong Yan et al. (44)	1	1	0	1	1	1	-	0	0	1	0	1	-	-	-	1	1	1	0	1	11
McPherson, Schrader, & Docherty (52)	1	1	0	1	1	1	-	1	0	1	0	1	-	-	-	1	1	1	0	1	12
Volkerding & Ketcham (42)	1	1	0	0	1	1	-	1	1	1	1	1	-	-	-	1	1	1	0	1	13
Hendry et al. (37)	1	1	0	0	1	1	-	1	1	1	1	1	-	-	-	1	1	1	0	1	13
Lee et al. (58)	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	0	1	14
Escobar Álvarez et al. (48)	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	0	1	14
Escobar Álvarez et al. (46)	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	0	1	14
Hendry et al. (36)	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	0	1	14
Perry et al. (49)	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	1	1	15
Peng et al. (56)	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	1	1	15
Imura & Lino (54)	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	1	1	15
Almonroeder et al. (53)	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	1	1	15

Harwood et al. (33)	1	1	1	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	1	1	16
Total / 29	26	25	3	16	22	29	-	23	18	20	16	20	-	-	-	23	17	20	7	24	-
Mean ± SD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10.7 ± 3

Intro. Introduction

Figure Captions

Figure 1 Flow diagram depicting the study search and selection process. Dance genre: studies excluded on the basis that participants were not primarily ballet dancers; Subject: studies excluded on the basis that kinetics or kinematics during take-off or landing phases of a jump were not assessed; Language: studies excluded on the basis that the article was not written in English; Type: studies excluded on the basis that they were not published original research (e.g., conference abstracts, letters, and reviews).


Identification
Screening
Eligibility
Inclusion
PubMed (MEDLINE) (n = 1191)
SPORTDiscus (n = 1893)
Web of Science (n = 697)
All records assessed for duplicates (n = 3781)
Records excluded (n = 1212)
Titles screened (n = 2569)
Records excluded (n = 2462)
Abstracts screened (n = 107)
Records excluded (n = 44)
Dance genre (n = 9)
Subject (n = 32)
Language (n = 1)
Type (n = 2)
Studies identified outside of the electronic database search (n = 7)
Full texts assessed for eligibility (n =70)
Records excluded (n = 41)
Dance genre (n = 35)
Subject (n = 3)
Type (n = 3)
Studies included in data synthesis (n = 29)