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Injury, Strength, and Jumping in Professional Ballet

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Injury, Strength, and Jumping in Professional Ballet

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ABSTRACT

Injury, Strength, and Jumping in Professional Ballet

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Jumping and landing activities are the most common mechanism of injury in professional ballet dancers. There is limited evidence, however, that has elucidated the moderators of load experienced when jumping and landing in ballet. This thesis aimed to describe injury epidemiology, establish reliable methods of assessing strength and jumping, and explore the factors that may influence lower extremity load during jump landings in professional ballet dancers.

A five-year injury epidemiology study revealed an incidence of medical attention and time-loss injuries of ~3–4 and ~1 per 1000 h of exposure, respectively. The mechanism of injury was jumping and landing activities in ~30–40% of time loss injuries. A systematic review found limited evidence that ballet dancers demonstrate externally rotated lower extremities, extended lower extremities prior to landing, and ankle-dominant jumping strategies.

Two methodological studies established the within- and between-session reliability of vertical ground reaction force (vGRF) across several maximal isometric force tests and three-dimensional ankle mechanics during landing in turnout and parallel foot positions. The reliability of vGRF during maximal isometric force tests across the squat, standing plantarflexion, and seated plantarflexion positions demonstrated excellent reliability (intraclass correlation coefficients (ICC): 0.92–1.00) and low variability (coefficient of variation (CV): 2.0–6.5%). Three-dimensional ankle mechanics demonstrated within- (ICC: 0.17–0.96; CV: 1.4–82.3%) and between-session (ICC: 0.02–0.98; CV:1.3–57.1%) reliability ranging from *poor* to *excellent*, with, ankle excursion, peak ankle angle, and jump height demonstrating the greatest ICC values (ICC: 0.65–0.96; CV: 1.4–57%).

The final two studies investigated jump landings in professional ballet dancers. A linear discriminate analysis revealed that three-dimensional ankle mechanics could discriminate different ballet foot positions, such that jump landings in fourth and fifth positions required a greater range of motion and ankle joint power when compared to other foot positions. Lastly, two linear mixed-effects models indicated that peak ankle joint moments and vGRFs have poor associations with strength, ankle dorsiflexion range of motion, and three-dimensional ankle excursions (R^2: 0.01–0.02). Sex, foot position, and individual variation are more appropriate factors to consider when assessing the load experienced at a joint or system level.

This thesis provides a thorough insight into injury, strength, and jumping in professional ballet dancers. To that end, this thesis has identified burdensome injuries and their mechanisms in professional ballet dancers alongside practical and reliable strategies to measure the physical attributes that may moderate the load experienced by a dancer upon landing.

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Thesis publications

Mattiussi AM, Shaw JW, Williams S, Price P, Brown DB, Cohen DD, Clark R, Kelly S, Retter G, Pedlar C, Tallent J. (2021) Injury epidemiology in professional ballet: a five-season prospective study of 1596 medical attention injuries and 543 time-loss injuries. *British Journal of Sports Medicine*.

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Related Publications

Shaw JW, Springham M, Brown DD, **Mattiussi AM**, Pedlar CR and Tallent J. The validity of the session rating of perceived exertion method for measuring internal training load in professional classical ballet dancers. (2020) *Frontiers in Physiology*.

Shaw JW, **Mattiussi AM**, Brown DD, Williams S, Kelly S, Springham M, Pedlar CR, Tallent J. Dance exposure, individual characteristics, and injury risk over five seasons in a professional ballet company. (2021) *Medicine & Science in Sports & Exercise*.

Shaw JW, **Mattiussi AM**, Brown DD, Springham M, Pedlar CR, Tallent J. (2021) The activity demands and physiological responses observed in professional ballet: A systematic review. *Journal of Sport & Exercise Science*.

Shaw JW, **Mattiussi AM**, Brown DD, Williams S, Springham M, Pedlar CR, Tallent J. (2023) Rehearsal and performance volume in professional ballet: a five-season cohort study. *Journal of Dance Medicine & Science.*

Katakura M, Kedgley AE, Shaw JW, **Mattiussi AM**, Kelly S, Clark R, Allen N, Calder JDF. (2023) Epidemiological characteristics of foot and ankle injuries in 2 professional ballet companies; a 3-season cohort study of 588 medical attention injuries and 255 time-loss injuries. *The Orthopaedic Journal of Sports Medicine.*

Shaw JW, Maloney B, **Mattiussi AM**, Brown DD, Springham M, Pedlar CR, Tallent J. (2023) The development and validation of an open-source accelerometry algorithm for measuring jump height and frequency. *Journal of Sports Sciences*.

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Maloney B, Shaw JW, **Mattiussi AM**, Price P, Cleather DJ. (2023) Jumping demands during classical ballet class. *Scandinavian Journal of Medicine & Science in Sports.*

Shaw JW, **Mattiussi AM**, Atack AC, Brown DD, Springham M, Pedlar CR, Tallent J, Cleather DJ. Lower limb tissue-specific force prediction during jumping and landing using inertial measurement units and recurrent neural networks. *In preparation.*

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Conference presentations

Mattiussi AM, Shaw JW, Williams S, Price P, Brown DB, Cohen DD, Clark R, Kelly S, Retter G, Pedlar C, Tallent J. Injury epidemiology in professional ballet: a five-season prospective study of 1596 medical attention injuries and 543 time-loss injuries. *International Association of Dance Medicine and Science 2021.*

Mattiussi AM, Shaw JW, Williams S, Price P, Springham M, Brown DB, Cohen DD, Clark R, Kelly S, Retter G, Pedlar C, Tallent J. Injury epidemiology in professional ballet: a five-season prospective study of 1596 medical attention injuries and 543 time-loss injuries AND dance exposure, individual characteristics, and injury risk over five seasons in a professional ballet company. *European Collage of Sports Science 2021.*

Mattiussi AM, Shaw JW, Williams S, Price P, Brown DB, Cohen DD, Clark R, Kelly S, Retter G, Pedlar C, Tallent J. Injury epidemiology in professional ballet: a five-season prospective study of 1596 medical attention injuries and 543 time-loss injuries. *The British Association of Sport and Exercise Sciences Conference 2021.*

Shaw JW, Mattiussi AM, Brown DD, Williams S, Springham M, Pedlar CR, Tallent J. The demands of a professional ballet schedule: a five-season study. *The British Association of Sport and Exercise Sciences Conference 2021.*

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LIST OF ABBREVIATIONS

CMJ	Countermovement jump
SD	Standard deviation
acc	Acceleration
Fz	Force
vGRF	Vertical ground reaction force
RFD	Rate of force development
BW	Body weight
BM	Body mass
F	Female
M	Male
NP	Non-professional
P	Professional
ND	Non-dancer
TO	Turn-out
FLEX	Flexion
EXT	Extension
PF	Plantarflexion
DF	Dorsiflexion
ABD	Abduction
ER	External rotation
MPJ	Metatarsophalangeal joint
AP	Anterioposterior
ML	Mediolateral
Exp	Experience
ROM	Range of motion
Ht	Height
J	Joules
deg	Degree
Max	Maximum
F-V$_{\text{IMB}}$	Force-velocity imbalance
EG	Experimental group
CG	Control group
+ve	Positive
PFP	Patellofemoral pain
PFJS	Patellofemoral joint stress
LAS	Lateral ankle sprain
CI	Confidence interval
m	meters
kg	kilograms
y	Year
h	hours
s	Seconds
App	Apprentice
F. Artist	First Artist
F. Soloist	First Soloist
PCA	Principal Character Artist

MA	Medical attention injury
TL	Time-loss injury
ICC	Intraclass correlation coefficients
CV	Coefficient of variation
MDC	Minimal detectable change
SL	Single leg
DL	Double leg

CHAPTER 1

Introduction

1.1 The Origin of Ballet

The origin of ballet dates back to fifteenth-century France, with the first ballet school (Royal Dance Academy) and the first professional ballet company (Paris Opera Ballet) being established in 1661 and 1672, respectively.[1] The Royal Ballet, on which this thesis is based, was founded in 1931 and is widely considered one of the world's foremost ballet companies and Britain's flagship company. Classical ballet, as a performing art, places great emphasis on the technical execution of choreography.[2] For example, alignment of the head, shoulders, and hips; turnout of the lower limbs; the *port de bras* (carriage of the arms); *pointe*; and *ballon* (light-footed while jumping) are some of the aspects of ballet technique that are considered to be important.[2] Further, there is a significant artistic component to classical ballet where dancers must portray a storyline, concept, or emotion. The physical demands of professional ballet training and performance have only recently been elucidated and are characterized by a high volume of *pliés*, leg lifts, *pas de deux* (partner lifts), and jumps.[3] To that end, it is unsurprising that the term "athletic artists" has been coined in recent years.[4] Increasingly, it is becoming commonplace for multidisciplinary science and medicine teams to be embedded within professional ballet companies and support their performance and rehabilitation.

1.2 A Professional Ballet Company

A dancer will undergo many years of training before successfully gaining a contract with a professional company. For example, The Royal Ballet has a structured system of training starting with the Junior Associates (age: 8–10), White Lodge (age: 11–16), and the Upper School (age: 17–19). Many dancers, however, will start ballet before the age of 8. The size of a ballet company can vary greatly depending on the resources available, such as funding, the number of practice studios, and the number of stages to perform on. For example, The Royal Ballet is a mid-to-large sized company that employs ~100 dancers compared to smaller companies such as Northern Ballet which employ ~40 dancers, or a large company such as Paris Opera Ballet which employs

~150 dancers. There is a hierarchical ranking structure that characterizes a professional ballet company. Although there will be subtle differences between ballet companies these ranking structures are largely similar. At The Royal Ballet, seven ranks make up the majority of the company (Table 1.1), although it should be noted that other ranks such as Guest Artists and Character Artists exist.

Table 1.1 An overview of the hierarchical ranking structure at The Royal Ballet

Rank	**Description**
Apprentice	Apprentices are typically on a one-year contract following their pre-professional training and will form part of the *corps de ballet* (ensemble)
Artist	Artists will be junior-ranking dancers that form the majority of the *corps de ballet*
First Artist	First Artists will form part of the corps de ballet but may dance some of the more featured aspects within this.
Soloist	Soloists will perform the solo roles or the minor featured roles within each ballet.
First Soloist	First Soloists will have a varied repertoire of the most featured soloist roles and they may perform some principal roles.
Principal	Principal dancers will be cast in the leading roles for each ballet and are considered the best dancers in the company.
Principal Character Artist	Principal Character Artists are typically older dancers who will perform in more artistic and less physically demanding roles compared to their counterparts. This may vary, however, depending on the production.

The schedule within a professional ballet company is typically made up of class, rehearsals, and performances.[5] Class—a cross between a technical training session and a daily warm-up—lasts ~75 minutes and is structured such that it becomes gradually more physically and technically challenging as it progresses. It starts at the *barre* (exercises while holding onto a rail) before moving into the centre where *adage* (slow enfolding movements), *petit allegro* (small jumps), and *grand allegro* (large jumps) are completed. Many dancers will refer to class as a warm-up regardless of the length and physicality of the session. Once class is complete, dancers will start their day of rehearsals. It is not uncommon to see dense rehearsal schedules of up to 6 hours per day that derive from multiple overlapping productions with numerous casts per production.[6] The rehearsal demands of each dancer within the same professional ballet company may be vastly different making it challenging to quantify workload. Lastly, A professional ballet company may perform a high volume of shows within a season, for example, The Royal Ballet performs ~135 shows on the main stage at the Royal Opera House between October and June. There is no typical microcycle structure of a week within some professional ballet companies as the shows per week can range anywhere from 0–8.

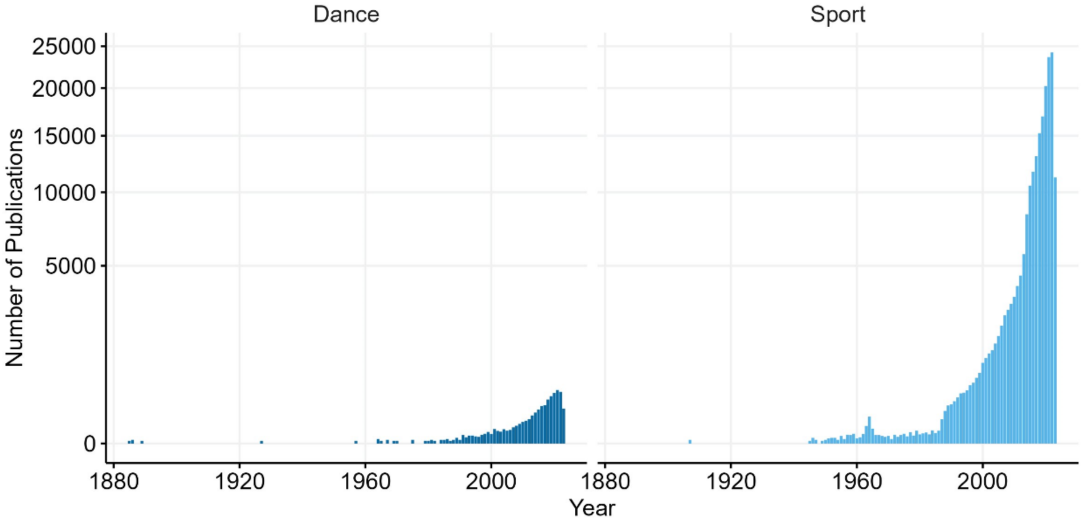


Figure 1.1 The count of results when "dance science" and "sports science" are entered into PubMed as search terms. The y-axis has been transformed using a square root transformation.

1.3 Science and Medicine in Ballet

Attempts have been made to standardise how medicine and science are implemented within a dance setting,[7] however, these do not typically align with similar efforts in sporting contexts.[8] It is perhaps unsurprising, therefore, that research in ballet—and dance more generally—is relatively limited when compared with sports. For example, a search of "dance science" on PubMed reveals 3,292 results since 1885, compared with 168,914 results using the term "sports science" (Figure 1.1). Nonetheless, in recent decades the volume of research in dance has steadily increased subsequently improving our understanding of different dance genres. Ballet—perhaps one of the more popular dance genres—has benefited from such research, providing new insights into this population and directing future investigations.

1.4 Jumping and Landing in Ballet

One particular area of growing interest in ballet is jumping and landing due to the associated volume with ballet training and the suspected risk of injury. Anecdotally, it is well established that a high rate of complex and technical jumping is commonplace in ballet. For instance, jumping occurs from foot positions which require extreme lower extremity external rotation, the aesthetic demands of ballet require relatively erect postures, and jumps can require gestures, beats, and rotations. All of these technical constraints influence the movement affordances available to the dancer, potentially increasing the load the system or specific joints are exposed to.

A conference paper published in 2006 outlining the rate of jumping during class has been a catalyst for further research investigating jumping and landing.[9] The aforementioned study has since been cited 59 times and is often used as a rationale within articles. Alas, the conference proceeding is inaccessible in the present day. More recent investigations into the rate of jumping during ballet performance[10] and the number of injuries of which the mechanism was attributed to jumping and landing actions[4] have rationalised recent research investigating jumping in ballet. Wyon et al.[10] documented a rate of jumping actions during professional ballet performance of ~5 jumps$\cdot$min^{-1}, a rate more than two-fold higher than that of contemporary dance performance. Additionally, Allen et al.[4] documented that ~25% of all injuries were attributed to jumping and landing actions in a professional ballet company.

1.5 Thesis Aims

There is a growing interest in jumping in ballet due to the volume,[10] technical requirements,[2] and associated injury risk.[4] Calls have been made—outside of dance science and medicine—to investigate jumping in more detail where it is a sport- (or dance-) specific requirement. Presently, there is limited evidence supporting the need to investigate jumping in professional ballet dancers. Further, the current landscape of research investigating the biomechanics of jumping and landing in ballet dancers is lacking a succinct review. Thus, the purpose of the present PhD thesis is split into three sections:

1. Describe the burden of injury in ballet and review what is currently known regarding jumping and landing biomechanics in ballet dancers
2. Develop reliable ways to assess the strength and landing mechanics of ballet dancers
3. Investigate the determinants of landing in professional ballet dancers

Chapter 2 explores on several areas of research given the broad nature of this thesis including injury epidemiology, the foot and ankle, and the measurement of strength in applied environments. Following Chapter 2, the thesis is separated into three sections with each section containing two individual chapters. An overview of the specific aims of each of these chapters is presented at the end of Chapter 2.

CHAPTER 2

Literature Review

2.1 The Cost of Injury

The cost of injury in sport and dance is real and can be viewed through several different lenses. In sporting populations, low availability, pre-competition injury, and in-competition injury have all been shown to increase the likelihood of failure to achieve key performance indicators across individual and team sports.[11] In a dance setting, this may result in individual dancers not fulfilling their potential such that they are not provided with new and challenging roles to dance, they are not promoted to more senior ranks, and they have lower financial rewards for their work. On a company level, the most suitable dancers for each role may not be available, negatively affecting the subjective success of a performance and the reputation of the organisation. Although not as tangible, an organisation's reputation will impact the level of government funding it receives,[12] the standard of dancers who wish to join, and the support offered through philanthropy.[13] An injury may also result in significant reductions in the psychological well-being of a dancer.[14] Wiese-Bjornstal[14] has discussed the negative cognitive, emotional, behavioural, and temporal aspects that an injury may have on an athlete, which include loss of identity, depression, a lack of adherence, and delayed return to play, respectively. Lastly, there is a financial burden of injury on the organisation in the form of the injured dancer's salary, medical bills (e.g., scans, operations, consultancy fees, etc.),[15,16] and a requirement for a larger company or drafting dancers in to cover. To that end, it is in the best interest of a dance company to minimise the risk of injury.

2.2 Injury Risk Management Frameworks

2.2.1 Sequence of Prevention Framework

The primary goal of a multidisciplinary science and medicine team is to reduce the risk of injury within the environment in which they work whilst improving performance. Various injury risk management frameworks have been developed to assist applied practitioners and researchers in reducing injury rates in sports (Figure

2.1).[17–19] Although such frameworks have not been developed specifically in dance, the application of sports injury risk frameworks in a dance context has been recommended.[7] van Mechelen et al.[18] developed the first sports injury risk management framework, the "sequence of prevention", which comprised of four steps: (1) establish the extent of injury incidence and severity; (2) establish aetiology and the mechanism of injury; (3) introduce preventative measures; and (4) assess the effectiveness of step three by repeating step one. The stepwise process outlined in this framework paved the way for injury prevention strategies, such as the Rugby Injury and Performance Project initiated in New Zealand in the 90s.[20–25]

2.2.2 TRIPP Framework

van Mechelen's framework was utilised for almost two decades before an updated framework was introduced by Finch, the "Translating Research into Injury Prevention Practice" (TRIPP) framework.[17] The TRIPP framework separates step three of van Mechelen's framework (introduce preventative measures) into two parts, identifying the need to (1) develop preventative measures and (2) evaluate the efficacy of such measures. Further, The TRIPP framework suggested an additional two stages that were omitted from van Mechelen's framework. Firstly, the context in which the prevention strategy is to be implemented should be understood to facilitate the implementation process (i.e., the motivations and barriers to uptake from key stakeholders). Secondly, the impact of the injury prevention measures—in conjunction with the implementation strategy developed from the feedback of key stakeholders—should be evaluated in the applied environment. The addition of stages that investigate the implementation context is of great value, as some contexts may have preconceived beliefs that will impact the uptake of an injury prevention intervention. For example, an educational intervention promoting the use of protective eyewear in squash players resulted in players having 2.4 times greater odds of wearing the appropriate eyewear thereafter.[26]

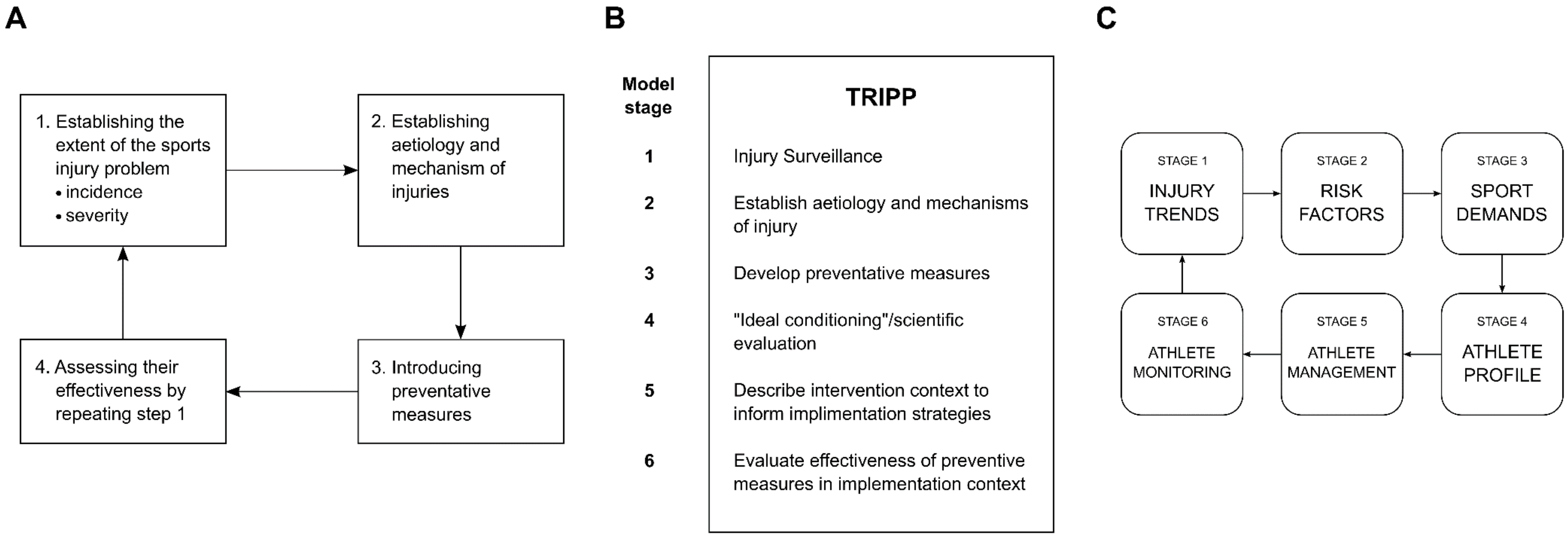


Figure 2.1 (A) Adapted from van Mechelen's four-stage "sequence of prevention" injury management framework.[18] (B) Adapted from Finch's "Translating Research into Injury Prevention Practice" injury management framework.[17] (C) Adapted from Roe's six-stage operational framework for individualising injury risk management in sports.[19]

2.2.3 Roe’s Injury Risk Management Framework

Another decade passed before the most recent injury risk management framework was introduced by Roe et al.[19] Although no limitations of the proceeding two frameworks were explicitly outlined, Roe et al. identified that injury prevention interventions are typically group-based and not individualised.[19] Accordingly, the framework adduced by Roe et al. dedicates two of it’s six-stages to creating a gap analysis. That is, to understand the demands of the sport (or dance genre) and the physical profile of the athlete (or dancer) before implementing an individualised injury prevention intervention. The outcome of such an intervention can then be monitored and the success evaluated. Curiously, Roe et al.[19] omitted the additional stage outlined by Finch,[17] which aimed to better understand the motivations and barriers to uptake within the implementation environment. The omission of this stage is unusual given the success of educational strategies to increase intervention uptake demonstrated in sports such as squash.[26]

2.2.4 Injury Risk Framework Summary

Where stages one and two appear to be consistent across all three frameworks outlined, the subsequent stages diverge thereafter. The differences observed in the later stages of Finch’s and Roe’s injury management frameworks may be explained by the target audience. Whereas the TRIPP is labelled as a tool to translate research into practice, it emphasises the requirement of broad research endeavours with the aim to impact applied practice.[17] Research conducted outside of applied environments will likely benefit from an additional stage outlining and addressing the contextual factors which may impact its implementation. Conversely, the framework outlined by Roe et al.[19] appears to target the applied practitioner by providing an individualised and evidence-based approach to injury risk management (i.e., not necessarily using formal research methods). The strengths of each framework should be noted, and, likely, a strategy that incorporates both contextual factors and an individualised approach into the intervention implementation process will have the most successful outcome when attempting to reduce injury rates.

2.3 Injury Surveillance and Epidemiology

2.3.1 Standardising Injury Surveillance

When establishing injury incidence and severity a universal injury surveillance system provides consistency in data acquisition and reporting that can facilitate comparison across sport and exercise.[27,28] Nevertheless, it is recommended that a sport (or dance) specific approach is adopted should an injury surveillance system aim to establish aetiological factors.[27,28] To that end, international consensus statements on injury (and illness) surveillance and epidemiology have been established in rugby,[29,30] soccer,[31] tennis,[32] cricket,[33] track and field,[34] endurance events,[35] multi-sport events,[36] aquatic sports,[37] horse racing,[38] and dance.[7] Recently, additional recommendations have been provided by international experts to further improve consistency in research methods when conducting and reporting injury epidemiology.[8,39] An extension to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) checklist was subsequently developed, the STROBE Sports Injury and Illness Surveillance (STROBE-SIIS) checklist.[8] Although the STROBE-SIIS is intended to strengthen the reporting of findings from observational studies, the authors acknowledge the relationship between study design and study reporting, and, as such, recommend its use during the planning phases of study design.

2.3.2 Injury Definition

The definition of an injury is one area that has received attention from international experts, as it is the first step towards the accurate calculation of injury incidence rates.[8,39,40] Clarsen and Bahr[40] argued that there is no “one size fits all” definition for injury (not to be confused with van Mechelen’s rhetorical question of “one size fits all?” in injury surveillance systems[28]), and, instead, introduced three operational definitions for recordable injury events (Figure 2.2). “Time-loss” (including “match time-loss”) is the most frequently used definition in observational research,[4,41–48] as it is easily identified by an inability to participate in pre-planned training and competition. The “time-loss” definition is typically used when calculating injury severity,[18] as severity can be defined as the cumulative days lost to a “time-loss” injury.[49] It should be noted, however, that there are other definitions for injury severity, such as the financial burden of the injury.[15] "Medical attention" represents a broader category of injury than "time-loss" and includes all events that have been assessed or treated by a medical practitioner, irrespective of participation in pre-planned training and competition. Further, "All complaints" includes all potential injury events and is perhaps most easily defined as capturing all medical events, including those that do not require assessment and treatment from a medical practitioner or changes in participation. "All complaints" and "medical attention" injury events have been suggested to be less reliable than "time loss" injury events, as medical support may not be uniform across all institutions and organisations.[40] For example, fewer "medical attention" injuries may be reported in an institute that has less medical support than an institute with more medical support.

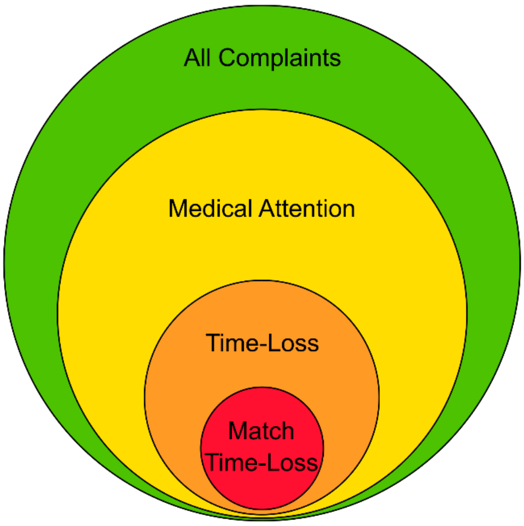


Figure 2.2 Interactions between various definitions of injury (and illness); adapted from Clarsen and Bahr.[40]

2.3.3 Exposure Definition

Once an injury definition has been established, the incidence rate can be calculated. A measure of exposure is required when calculating the injury incidence rate for any sport or dance genre.[8] The injury incidence rate is usually reported as the count of injuries per 1000 hours of exposure, however, exposure can be expressed as a count of exposure events or athlete seasons where accurate exposure hours are not available.[8] Reporting injury incidence rates consistently across sports and dance genres allow science and medicine practitioners to compare and evaluate the risks of their unique environment against others. The calculation of incidence rates can also be applied to different groups within an environment to identify high-risk individuals. For example, forwards and backs in rugby union,[41,50] men and women in beach volleyball,[51] or across company rank in professional ballet.[4] Incidence rates can also be used to calculate the burden across the anatomical region and tissue type, facilitating the identification of injuries that pose the greatest strain on medical departments. Hamstring strains in track and field[52] or concussions in rugby union[53] are examples where sport-specific injuries have been identified and investigated further to improve player well-being and minimise the burden placed on medical departments.

2.4 Mechanism of Injury and Injury Risk Factors

2.4.1 Mechanism of Injury Definition

Identifying the mechanism of injury is a key component of injury management frameworks.[17–19] Whiting and Zernicke[54] define the term “mechanism of injury” as “the fundamental physical process responsible for a given action, reaction, or result”. The term mechanism of injury is typically associated with the inciting event immediately prior to injury and can be sport- or dance-specific. For example, sport-specific mechanisms of injury in ice hockey include body checking, being hit by the puck, and even fighting.[55] Conversely, dance-specific mechanisms of injury in professional ballet include inciting events such as jumping and landing, arabesque, and *pointe*.[4] Although the inciting movement pattern is important, the mechanism of injury can be described in greater detail where data are available. The mechanism of a lateral ankle sprain injury, for example, can be described across the context (e.g., choreography with a fast tempo and intricate footwork), the dancer/athlete behaviour (e.g., the dancer attempting the variation ‘full out’), the global dancer/athlete biomechanics (e.g., landing from a jump) and the local tissue biomechanics (plantarflexion/inversion moment on the ankle).[56]

2.4.2 A Biomechanical Approach to Injury

A biomechanical approach to understanding the mechanism of injury considers the physical load applied to a tissue and the load-capacity of said tissue. Biological tissue such as bone, ligament, muscle, and tendon have different material properties based on their extracellular matrix,[57] and, thus, will respond differently to the same physical load.[58] Further, the response of the tissue will depend on the rate, magnitude, and frequency of the physical load applied to it.[59] The primary outcome when using a biomechanical approach to understanding injury mechanisms is to establish either: how an inciting event may result in a physical load that surpasses a tissue's normal capacity; or how an inciting event may result in a reduction in a tissue's normal capacity, resulting in failure.[60] For example, in rugby union, a collision with a player of the opposite team may result in a valgus moment on the knee that surpasses the anterior cruciate ligament (ACL) tensile strength, leading to rupture. Conversely, a ballet dancer may suffer a tibial stress fracture from repetitive landing, low bone mineral density, a poor ability to attenuate energy, and inadequate recovery time.

2.4.3 Injury Risk Factors

It should be noted that intrinsic factors such as age, sex, and physical fitness may impact the interaction between physical load and biological tissue.[60] For example, habitual loading has resulted in hypertrophy of ligaments within the knee,[61,62] which may reduce the risk of tissue failure through an improved ability to tolerate external forces.[63,64] Further, extrinsic factors such as floor surface properties, footwear, and weather may also impact the interaction between physical load and biological tissue.[56] For example, a higher injury incidence rate was observed in female handball athletes when playing on artificial floors compared with wooden floors, potentially due to the higher friction associated with artificial floors.[65] The term "risk factors" has been coined where associations between injury and internal and external factors have been identified.[66] Various models have been developed to better understand the relationship between injury events, risk factors, and the mechanism of injury.

2.5 Injury Aetiology and Injury Risk Factor Models

2.5.1 Injury Risk Factor Models

Meeuwisse[66] developed the first multifactorial model of injury aetiology in the 90s (Figure 2.3), illustrating how intrinsic and extrinsic risk factors might interact with the athlete to result in an injury. To the author's knowledge, a further six models have been introduced or updated since,[56,60,67–70] with the most recent model established by Bittencourt et al (Figure 2.4).[69] A detailed description of each model is outside the scope of this literature review, however, the shift in model emphasis has been towards embracing a complex systems approach. A complex systems approach is a method that studies how the interactions between a system's individual parts give rise to the behaviours of the system. To date, however, a large proportion of sports injury research has used a reductionist approach.[71] A reductionist approach is an alternative paradigm to a complex system approach, where individual parts of a system are investigated in isolation. Reductionism, although limited in its ability to predict injury, has identified individual risk factors associated with injury. Bittencourt et al,[69] however, described sports injury as a complex system, where it: is an open system (risk factors interact with the environment), possesses non-linearity (interactions between risk factors are non-linear), relies on a recursive loop (system outputs are processed and become inputs), self organises (emerging behaviours can not be predicted based on the individual components), and contains uncertainty (relies on probability over causation).

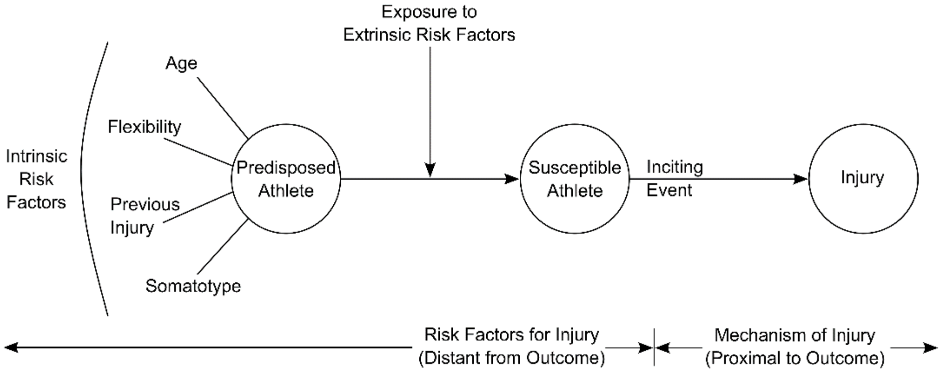


Figure 2.3 Adapted from Meeuwisse's multifactorial model of athletic injury aetiology.[66]

2.5.2 Complex Systems

Adopting a complex systems approach is challenging, as data analysis requires the application of advanced statistical methods such as machine learning.[72] The lack of adoption may, in part, be due to many sport and exercise researchers not having the requisite skillsets to apply such statistical computation. Indeed, the lack of statistical knowledge in sport and exercise research has been acknowledged and collaboration with statisticians has been recommended.[73] Another challenge when investigating injury risk factors using a complex system approach is the sample size requirement—a large number of injuries are necessary to apply machine learning techniques.[72] Such sample sizes are often not practical in applied environments and may require years of data collection or multicentre collaboration where data are pooled to meet the requisite power.[74] Nonetheless, machine learning techniques have been successfully applied to investigate ACL injury risk factors in the context of a complex system, even in the absence of injury data.[75] For example, frontal plane knee angles during landing have been identified as a mechanism for ACL injury.[76] Non-linear interactions between lower extremity strength, range of motion, and dynamic alignment have been used to predict frontal plane knee angles during landing.[75] Investigating the relationships between potential risk factors and proxy outcome measures for injury (such as frontal plane knee angles in ACL research) instead of injury, offers a realistic strategy for the adoption of a complex systems approach. Alas, there will still be important information omitted for such analyses that may contribute to the status of a tissue's health and its vulnerability to injury.

2.6 Injury Risk Factors and Jumping

Jumping places notable demands on the lower extremity.[77–81] To that end, jumping and landing activities have been identified as a common mechanism of injury in sport and professional ballet,[4,82] and calls for further investigation into such actions have been made.[83] It should be noted, however, that many studies investigating injury in professional ballet have not reported injury mechanisms,[15,16,46,84–86] and, as such, evidence to support jumping as a primary injury mechanism is currently limited. Nevertheless, understanding the risk factors associated with jumping and landing may provide novel insights into lower extremity injury in professional ballet dancers. Indeed, epidemiology research in professional ballet dancers has identified that a large proportion of the injuries sustained are located around the foot, ankle, and shank,[4,84,85] which may be a specific area for further investigation within this cohort.

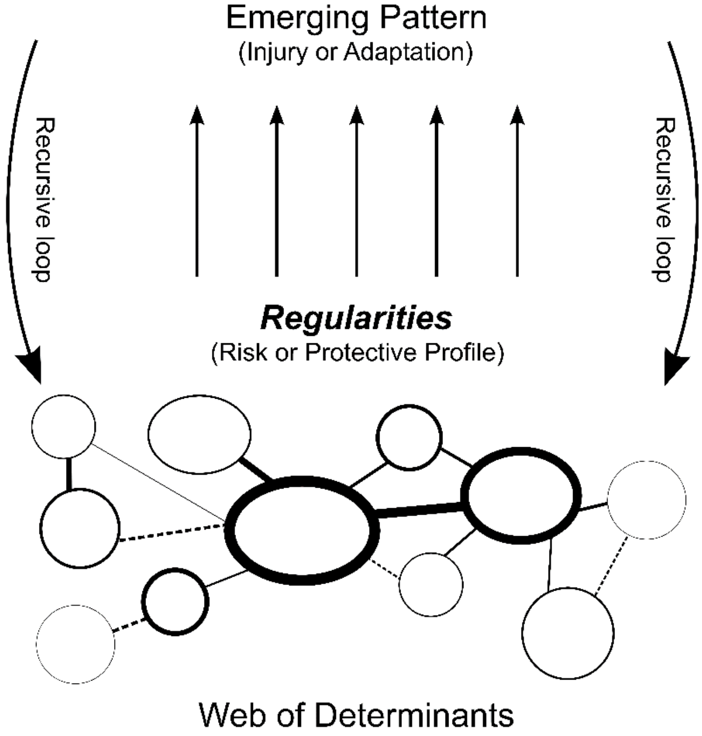


Figure 2.4 Adapted from Bittencourt et al.'s complex model for sports injury.[69]

2.6.1 Mechanical Fatigue and Injury

Edwards[87] discussed how repetitive loading cycles of biological tissue—such as a high volume of landings on tibial cortical bone properties—can result in tissue failure consistent with a mechanical fatigue process (Figure 2.5). Further, changes in the magnitude of loading, as opposed to the number of loading cycles, increase the risk of overuse injury more rapidly.[87] When considering the conceptual framework outlined by Edwards[87] (Figure 2.5), it is possible to influence injury at different stages. The volume/duration of loading cycles and the remodelling/adaptation component are two modifiable stages. Appropriate management of training load may have a positive impact on overuse injury such that repetitive loading cycles of high-risk activities are avoided and regular periods of rest and recovery are provided to facilitate remodelling and adaptation where damage is incurred. Alas, the training load in professional ballet is consistently high due to the number of productions per season, the number of casts for each production, and the subsequently dense rehearsal schedule.[5] Unlike a sporting context, many dancers will not share consistent schedules, and, as such, the management of training load across a large cohort of professional ballet dancers can be challenging. To that end, the management of training load in a professional ballet setting has been discussed extensively elsewhere and is outside the scope of this thesis.[88]

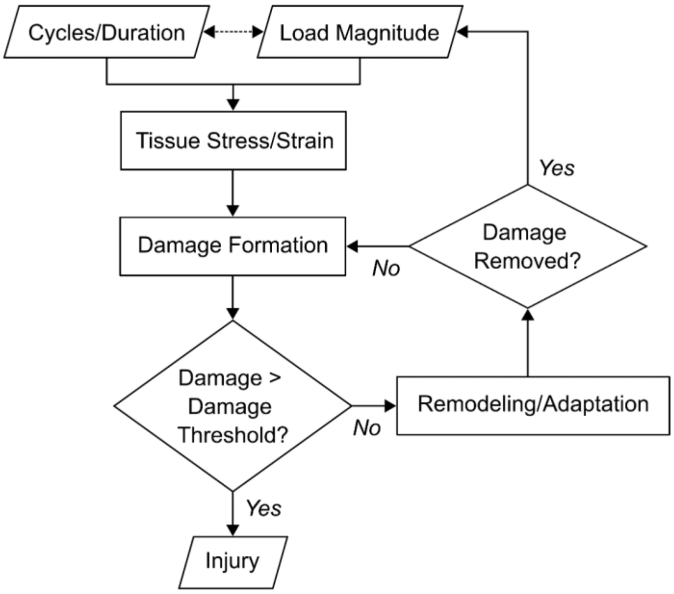


Figure 2.5 A conceptual framework outlining how mechanical fatigue can lead to overuse injury (adapted from Edwards[87]).

It is possible to reduce the magnitude of loading during specific discreet skills associated with injury, such as landing activities. In sport and exercise literature, various authors have attempted to investigate the intrinsic factors that mediate the magnitude of load experienced while landing from a jump or the dynamic joint alignment of the lower limb upon landing, as a proxy for injury risk.[75,89–93] For example, modifiable factors that influence the magnitude of vGRF during landing include dorsiflexion range of motion,[94–97] strength,[75,89–93] lean body mass,[91] proprioception,[92] lower limb flexion angle,[98–100] the sound characteristics of the landing,[101] foci of attention,[102,103] and drop height.[104,105] As such, interventions to improve dorsiflexion range of motion (ROM), increase lower limb strength, or utilise strategies that increase lower limb flexion angle have been integrated into applied environments to reduce the magnitude of load at a system (e.g., vGRF) or a joint level (e.g., joint mechanics). The association between strength, ankle dorsiflexion ROM, dynamic joint alignment, and load experienced by the lower limb has not yet been investigated in ballet dancers. Such investigations may provide practitioners with practical methods of profiling ballet dancers and guidance when writing physical development programs in the context of injury, particularly as the foot, ankle, and shank are common areas of injury.[4,84,85]

It should be noted, however, that it is not always possible to manipulate intrinsic factors in real-time as time constraints, technical requirements, or external influences may affect the movement affordances available to dancers while landing. For example, a dancer may be unable to reduce vGRF through more pliable landings because the choreography and the tempo of the orchestra are too fast to facilitate such a strategy. It may therefore also be of interest to provide dancers with the physical characteristics which allow them to better tolerate the demands of landing activities.[56] The material properties of various soft tissues—such as muscle, tendon, ligament, and bone—are adaptable and the capacity of these tissues to tolerate stress and strain can be increased.[61,106] Resistance training interventions can facilitate such adaptations and the assessment of strength can provide a proxy for these adaptations.[61,107,108] Other aspects include the fundamental codified foot positions in which dancers will take off and land during every jump (Figure 2.6). These foot positions introduce unique challenges to the lower extremities and only two studies have compared them, focusing their analyses on parallel and first.[80,109] It should be noted, however, that many more studies have investigated ballet-specific jumps in isolation.

2.7 The Foot and Ankle

More than 50% of all injuries in professional ballet occur around the distal lower extremity (the foot, ankle, and lower leg).[4,84–86,110] As such, it is important to understand the anatomy and physiology of this region, alongside the mechanisms of injury, to fully appreciate the injury risk factors, gaps in knowledge, and how best to implement injury prevention programs.

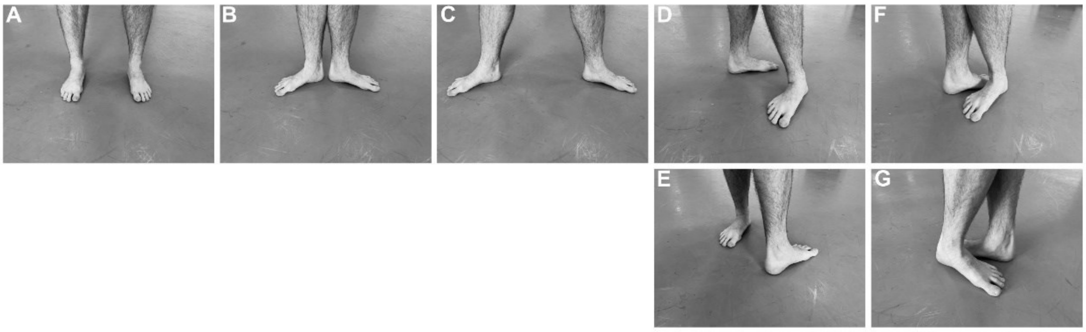


Figure 2.6 An overview of the codified foot positions in classical ballet with reference to parallel. A) parallel; B) first; C) second; D) and E) are both fourth position; F) and G) and both fifth position. Third position was omitted as it is typically not coached in a professional setting.

2.7.1 Anatomy of the Foot and Ankle

The foot and ankle complex is made up of 26 bones including the phalanges, metatarsals, tarsals (talus, calcaneus, cuboid, navicular, and cuneiforms), tibia, and fibula.[111] Collectively these bones make up 31 joints;[111] of which the subtalar, talocrural, and talocalcaneonavicular joints are most commonly referenced when discussing the joints with the greatest ROM available.[112] It should be noted that these joints do not work in isolation and will all contribute to the ROM available to the foot and ankle.[113] For example, the talocrural joint can be considered the primary joint that facilitates ankle dorsiflexion due to its hinge-like nature, however, it is accepted that other joints, such as the subtalar joint, will also facilitate dorsiflexion.[113,114] Aside from the bony anatomy, there is a multitude of passive and active restraints that influence the function of the foot and ankle during sport and exercise including joint capsules, ligaments, and muscles.[111,112]

2.7.2 The Dancer's Foot and Ankle

Extreme foot and ankle ROM is a characteristic of professional ballet dancers and can be observed during almost all discreet skills within a piece of choreography (Figure 2.7).[113,115] For example, it is typical for the foot and ankle complex to be in maximal plantarflexion during all open kinetic chain skills for aesthetic reasons (i.e., a pointed foot is more aesthetically pleasing than a flexed foot in classical ballet technique). During closed kinetic chain skills, such as *demi-pointe* or *pointe*, the ankle will be maximally plantarflexed but the metatarsophalangeal joints will be in relative extension or flexion, respectively. The bony geometry of ballet dancers' ankles appears to adapt to such specific tasks, with a merging of the posterior tibial plafond, posterior talus, and superior calcaneus.[115] Ballet dancers also require large degrees of ankle dorsiflexion, as classical ballet technique favours upright postures during discreet skills (such as jumping and landing) that bias the ankle and knee as opposed to the hip.[80]

Figure 2.7 A visual indication of the extreme range of motion available at the ankle during movements utilising both an open and closed kinetic chain in professional ballet dancers.

2.7.3 Biomechanics of the Dancer’s Foot and Ankle

In dancers, ankle joint moments typically contribute ~26–31% of the total support moment when landing.[116] Where the ankle mechanics of male and female dancers (of mixed genres) have been investigated, few differences have been observed. For example, no differences in sagittal or frontal plane joint kinematics were observed between men and women during a 30 cm drop landing with both sexes utilising ~52° of ankle dorsiflexion.[116] Further, no differences in sagittal or frontal plane joint moments at initial contact (0.2 $Nm\cdot kg^{-1}$), peak knee flexion (~1.2 $Nm\cdot kg^{-1}$), and peak joint moment (2.0 $Nm\cdot kg^{-1}$) were observed either.[116] It should be noted that these findings (i.e., a lack of differences between men and women) were consistent across the entire kinetic chain and not isolated to the ankle.

Where dancers (of mixed genres) have been compared to college-level team sport athletes, no differences in dorsiflexion at peak ankle moment have been observed (dancers: ~9°; athletes: ~5–11°). Greater sagittal plane ankle excursions were observed in dancers compared to athletes, likely due to greater plantarflexion angles at initial contact.[117,118] Given that excessive ankle plantarflexion and inversion are a mechanism for lateral ankle sprains,[119–122] this data may provide context to traumatic injury risk factors in dancers. No significant differences have been observed in ankle joint moments during landing, however, men typically demonstrate greater values compared to their female counterparts.[117]

Dancers also demonstrated lower ankle stiffness values compared to athletes, suggesting that their landing strategy is more compliant.[117] Previous authors have suggested that the findings observed between male and female dancers and athletes indicate that engagement in jump-specific training from a young age—as observed in dance—may account for the disparity in landing biomechanics as opposed to intrinsic sex differences.[116,117,123,124] The aforementioned landing strategy was during a single jump-landing, however, and, repeated jumping actions may result in a different strategy. For example, the utilisation of elastic energy typically requires greater stiffness, often characterised by short ground contact times and a less compliant lower extremity.[125] The benefit of greater stiffness in the context of professional ballet is reducing the epoch between eccentric and concentric muscle contractions in the presence of a fast-tempo piece of music. Further, the efficiency of isometric contractions (compared to longer eccentric and concentric contractions) will minimise the fatigue experienced by the dancer.[125]

Presently there is limited literature that has investigated lower extremity biomechanics comparing various multiplanar jumps, with none describing ankle joint kinetics. Azevedo et al.,[118] investigated forward, diagonal, and lateral jump landings in professional (mixed genre) and non-professional dancers and observed 2 and 4 degrees greater ankle inversion angles at initial contact during diagonal and lateral jump landings, respectively. Peak ankle angles and moments will likely vary during rotational jumps which may have implications for injury both at the ankle and further up the kinetic chain. Given that rotational jumps can occur in both directions (*en* *dehors* and *en dedans*) there may also be specific considerations for each, for example, *en dedans* is a jump in the direction of the supporting leg which may result in a greater vagus moment on the knee joint.[126] Conversely, *en dehors* is away from the supporting leg and may place a greater inversion moment on the ankle.[119–122] Such considerations may influence injury prevention strategies such that motor control, strength, and fatigue are optimised during choreography requiring these techniques.

2.7.4 Assessment of Ankle Dorsiflexion

Ankle dorsiflexion ROM is important across numerous discreet skills that require triple flexion of the lower extremity—such as jumping and landing—as it directly influences the ROM utilised at the knee and the hip,[127,128] and may mediate the forces experienced at the ankle.[95,96] To that end, it is important to be able to reliably measure ankle dorsiflexion ROM, and, where appropriate, apply an intervention to improve it. Ankle dorsiflexion is often measured utilising one of two methods; a weight-bearing lunge[95] or an isolated passive ankle dorsiflexion ROM assessment.[94,129] Both methods have demonstrated excellent within-session reliability, however, no literature has reported the between-session reliability of either of these tests.[130–132] The isolated passive assessment of ankle dorsiflexion typically yields smaller dorsiflexion values when compared to the weight-bearing lunge, potentially due to the stiffness of local structures being greater than the force the clinician is able to exert onto the joint.[94,95,129] The assessment of isolated passive ankle dorsiflexion ROM may be challenging to standardise between practitioners as ROM is determined by the amount of force applied to the joint. Similar issues have been identified when utilising hand-held dynamometry (HHD) to assess the strength of isolated joints.[133] The weight-bearing lunge assessment may therefore provide a more reliable method of ankle dorsiflexion assessment.

2.7.5 Interventions to Improve Ankle Dorsiflexion

Where interventions have been developed to improve ankle dorsiflexion, much of the literature has focused on stretching, with static stretching (< 30 minutes) and proprioceptive neuromuscular facilitation demonstrating the greatest increases in ankle dorsiflexion ROM compared with ballistic stretching or stretching for longer durations.[132,134,135] Other methods, such as using a non-elastic strap around the talus and 10° incline board to facilitate the arthrokinematics of the ankle have also shown increases in ankle dorsiflexion ROM.[136] This technique utilises a strap to exert an anterior-posterior force on the talus during active dorsiflexion. It is thought that this anterior-posterior force facilitates the optimal glide of the talus between the tibia, fibula, and calcaneus and, in turn, restores dorsiflexion ROM.[137] Further, resistance training, static stretching, and self-mobilisations using a strap combined have demonstrated increases in ankle dorsiflexion ROM.[96] It is likely that in applied environments all of these techniques will be employed when aiming to improve ankle dorsiflexion in an athlete or dancer.

2.8 Adaptations to Resistance Training

2.8.1 Broad Adaptations

The adaptations to resistance training encompass a variety of neural, hormonal, and morphological changes to the target tissues.[107,108,138,139] Initial adaptations following four weeks of resistance training are predominantly neuromuscular, resulting in changes such as increased rate coding, doublet firing, a reduced threshold for motor unit recruitment, improved motor unit synchronisation, and an improved relative output to input gain of motor neurons.[138,140–144] Increases in muscle cross-sectional occur following medium- and long-term resistance training interventions and typically play the primary role in strength development after the initial neurological adaptations.[145–149]

2.8.2 Additional Adaptations

Additional morphological adaptations occur as a consequence of resistance training. Changes in muscle phenotype can occur within the initial four weeks of a resistance training intervention in men and women, with a relative decrease in the percentage of type IIb muscle fibres.[108] It is also possible to enhance the mechanical properties of non-contractile tissues—such as tendons, ligaments, and bones—following habitual resistance training.[150] The mechanical properties of soft tissues are largely dependent on the size and structure of their extracellular proteins such as type I collagen, fibrillin, and elastin.[151–153] Beaulieu et al.[61] found that athletes who engaged in sports with a unilateral bias (figure skaters and springboard divers) demonstrated an ACL and a patella tendon with a larger cross-sectional area on the biased side. Tendon adaptation following resistance training has been studied extensively due to the injury burden associated with tendinopathy.[154–156] Tendons with larger cross-sectional areas and a higher density of type I collagen, as a consequence of resistance training, also tend to have a higher youngs modulus and stiffness, improving their ability to tolerate stress and strain.[157] Chilibeck, Sale, and Webber[158] reviewed the effects of exercise, including resistance training, on bone mineral density and summarised that strength-trained athletes have a higher bone mineral density when compared to non-athletes. Further, associations between strength, muscle mass, and bone mineral density have been observed following longitudinal resistance training.[158]

2.8.3 Resistance Training and Injury

It is plausible to consider that tissues with greater tolerance to stress and strain—as a consequence of resistance training—may be more resilient to both traumatic and overuse injury.[87] It should be noted, however, that as soft tissues adapt to resistance training and increase their ability to generate higher forces or be exposed to stress and strain, they will likely be exposed to higher energy impacts more frequently as a consequence. For example, a lower limb resistance training program may be implemented to reduce the risk of injury in a dancer,[46] yet it may result in a dancer's vertical jump increasing which may expose them to greater landing forces more frequently.[159,160] It is important, therefore, that resistance training programs are implemented alongside appropriate technical training to ensure that physiological adaptations are integrated alongside desired landing biomechanics. In the absence of specialist equipment to directly measure neurological, hormonal, and morphological adaptations to resistance training, it is feasible to use maximum strength as a proxy for such adaptations.

2.9 Assessment of Maximum Strength

Maximum strength can be defined as the maximum amount of force that an individual can produce during isometric, eccentric, concentric, or coupled muscular contractions across single or multiple joints.[161] There are various ways of assessing maximum strength including repetition maximum testing, isometric force testing, hand-held dynamometry, and isokinetic dynamometry. The choice of assessment method in applied practice may be influenced by several factors, such as the resources one has access to, the time associated with the testing method, the skill required to execute the test, and how well that test can be standardised (Table 2.1).

2.9.1 Isokinetic Dynamometry

Isokinetic dynamometry is a unique form of strength assessment as it maintains a specific speed of contraction throughout the testing range of motion. This differs from all other testing methods where contraction speed is not pre-determined and is auto-regulated by the participant. The benefit of such testing is the ability to produce accurate force- (or torque-) velocity profiles across the joint or muscle group of interest.[162] The basis for such testing is to replicate the high-velocity contraction types that are associated with various performance tasks and injury mechanisms. Isokinetic dynamometry not only facilitates concentric and eccentric contraction types but also angle-specific isometric contractions.[163] Isokinetic dynamometry is considered the gold standard when assessing the strength characteristics of an isolated joint and is often used as a reference standard to assess the validity of other assessment tools or protocols.[164–166] It is considered the gold standard because it is highly standardised; you can isolate a single joint, through a single plane, across a fixed range of motion, at a set speed. As a consequence, isokinetic dynamometry has been deemed to be a highly reliable testing tool.[167] Further, no previous experience or skill is required from participants who undertake isokinetic dynamometry, as there are fewer degrees of freedom compared to other testing methods, such as repetition max testing using free weights. Nevertheless, there are several limitations to isokinetic dynamometry, namely the initial cost, the space requirements, the time associated with setting up the equipment, and its ecological validity. The set-up time is significantly reduced in isokinetic machines that are designed to only test a single joint, such as the knee, as opposed to a machine that can test all joints across the kinetic chain. The price of the equipment is a common reason why researchers aim to validate more cost-effective methods of strength assessment.[168] Further, many organisations may not prioritise space to house an isokinetic dynamometer, particularly if testing is relatively infrequent. Although, isokinetic dynamometry lacks ecological validity, this is likely not a unique feature and all measures of maximum strength will compromise specificity for a position in which higher forces can be observed.

2.9.2 Repetition Maximum

The repetition maximum (RM) method is a common strategy employed within applied environments to quantify progress or assess physical status at a given point in time. The 1RM test is typically cited within the literature,[161] however, calculations have been developed to predict 1RM using a submaximal load such as a 3, 5, or 8RM.[169–173] Submaximal testing has been used in place of 1RM testing as it is deemed to be safer in certain populations and more time efficient.[172,173] Many strength and conditioning coaches will favour the repetition maximum method as it facilitates the accurate calculation of submaximal loads that can be used for training prescription. Further, no additional equipment is required to conduct repetition maximum testing, saving both space and time compared to other methods, such as isokinetic dynamometry. The limitations of the repetition maximum method, however, are that standardisation between participants is challenging during certain exercises. For example, the back squat is a common method of assessment because it is a compound exercise with an emphasis on lower extremity triple extension, resulting in a high dynamic correspondence to various performance tasks.[174–176] Standardising the range of motion during the squat between participants is challenging due to differences in anthropometrics, boney geometry, flexibility, and technical skill. Nonetheless, 1RM testing has been deemed reliable within participants.[161] Further, a participant's technical skill may impact their ability to execute 1RM testing safely and efficiently, particularly during free-weight exercises such as the back squat.[177] It is safe, however, to utilise fixed resistance machines to conduct repetition maximum testing due to the reduced degrees of freedom (i.e., fixed range and planes of motion).

2.9.3 Hand-Held Dynamometry

Hand-held dynamometry is a popular method of isometric strength assessment in clinical settings, potentially because it is an objective method of manual muscle testing.[178] Manual muscle testing is a typical component of a musculoskeletal physiotherapy assessment but has historically been conducted subjectively.[179] Hand-held dynamometry has several strengths when compared to other testing methods as it is relatively inexpensive, it is fast to implement, requires minimal space to conduct testing or store equipment, and has a low skill requirement from the participant. The primary limitation of HHD, however, is that it is challenging to standardise between examiners and that in some positions the participant can overpower the tester.[133,180] This is likely a consequence of different testing procedures. There are two forms of testing procedure: the ‘make test’ and the ‘break test’. The make test is where the tester instructs the participant to maximally contract into the HHD, whereas the break test is where the tester will apply as much force as necessary to compromise the specified testing position. To that end, HHD has been criticised and attempts have been made to utilise the dynamometer in contemporary ways where it is fixed in place such that the examiner is removed from the equation.[133,181] Consequently, notable improvements in reliability have been observed when the HHD is fixed in position.[133,181]

2.9.4 Isometric Force Testing

Isometric force testing has gained notable popularity in recent years. Original research has demonstrated the reliability and validity of different positions that bias different joints and musculature, as well as assessing the association with various performance tests.[161,182,183] The reliability of peak vGRF measures has consistently been high, often with intraclass correlation coefficients above 0.9.[182,183] To that end, isometric force testing is easy to standardise within and between participants, particularly when using a fixed rig with set rack heights. Standardisation becomes more difficult within participants when other techniques, such as seat belts, are used as joint angles must be measured on every testing occasion. Nonetheless, the speed of assessment when utilising isometric force testing, compared to other methods of strength assessment, is a primary reason for adoption in applied settings.[184] The drawbacks of isometric force testing include the financial burden and the limited ability to use the result (i.e., peak vGRF) to prescribe submaximal training loads. The financial burden of integrating force-time analyses into applied settings is becoming less of a barrier with the innovation of new technologies into force platform technology, such as force beams as opposed to piezoelectric crystals.[185] The majority of the cost of such platforms can now be attributed to the automated software, with costs being even lower where practitioners are able to complete the integration process manually.[186,187] It is possible to prescribe submaximal training loads when utilising isometric force testing but only when the training modality is isometric, which may not always align with the training modalities selected by the practitioner writing the program. Thus, normative data are key when interpreting results to make an informed decision on whether an athlete or dancer should direct their focus to strength development compared to other physical qualities.

Table 2.1 An overview of the pros and cons associated with different strength assessment methods.

Assessment Method	Time	Cost	Space	Skill	Standardisation
Isokinetic Dyamomentry	✗	✗	✗	✓	✓
Repetition Maximum	✗	✓	✓	✗	✗
Hand Held Dynamometry	✓	✓	✓	✓	✗
Isometric Force	✓	✗	✓	✓	✓

Time refers to the time associated with the set-up and testing procedures of the assessment method. Cost refers to the cost of the assessment method. Space refers to the space requirements to house the equipment needed for the assessment method. Skill refers to the skill requirements of the participant being tested. Standardisation refers to the reproducibility of the assessment method.

2.10 Thesis Overview

This thesis is organised into three sections (Figure 2.8). Two chapters sit within each section and are outlined below with a specific research question at the start of each paragraph. A broad literature review precedes the first section, following an introduction to the thesis.

2.10.1 Section 1: Understanding the Problem

Chapters 3 and 4 develop a rationale for further investigation into jumping and landing in professional ballet dancers.

2.10.1.1 Chapter 3: Injury Epidemiology in Professional Ballet: A Five-Season Prospective Study of 1596 Medical Attention Injuries and 543 Time-Loss Injuries

What are the epidemiology and aetiology characteristics of a professional ballet company?

Chapter 3 is a five-year study that investigates the incidence, severity, and burden of medical attention and time-loss injuries in professional ballet dancers. Critically, aetiology factors such as injury location and injury mechanisms are described, supporting previous work and providing a basis for future research in this area. This is the most comprehensive injury epidemiology study within professional ballet and follows the guidelines provided by the STROBE-SIIS.

2.10.1.2 Chapter 4: Jumping in Ballet: A Systematic Review of Kinetic and Kinematic Parameters

What is currently known about the biomechanics of jumping in ballet dancers?

Chapter 4 is a systematic review reporting the current body of work that has investigated take-off and landing biomechanics in ballet dancers. Included studies were categorised into six themes to facilitate interpretation: Activity Type, Environment and Equipment, Demographics, Physical Characteristics, Injury Status, and Skill Acquisition and Motor Control. As part of the inclusion criteria, this chapter included any study that investigated the biomechanics of ballet dancers during jumping activities. As such, studies investigating both non-professional and professional dancers were included. Twenty-nine studies were included in the review and the results are synthesised and discussed.

2.10.2 Section 2: General Methods

Chapters 5 and 6 form a general methods section in which the reliability of lower extremity isometric force tests and jump landings in parallel and turned-out positions is established.

2.10.2.1 Chapter 5: Reliability, Variability, and Minimal Detectable Change of Bilateral and Unilateral Lower Extremity Isometric Force Tests

Are lower extremity isometric force tests reliable?

Chapter 5 establishes the within- and between-session reliability, variability, and minimal detectable change of bilateral and unilateral variations of isometric strength tests across the squat, standing plantarflexion, and seated plantarflexion positions. Intraclass class correlation coefficients and coefficients of variation are used to establish the reliability and variability of vertical ground reaction force for each test, respectively. Due to challenges with recruitment, a sub-sample of eight participants out of the total eighteen participants are professional ballet dancers and the remaining ten are made up of the general population.

2.10.2.2 Chapter 6: Reliability of Ankle Mechanics During Jump Landings in Turned-Out and Parallel Foot Positions in Professional Ballet Dancers

Are joint mechanics and vGRF during jump landings in parallel and turned-out foot positions reliable in professional ballet dancers?

Chapter 6 established the within- and between-session reliability, variability, and minimal detectable change across ankle mechanics and vGRF during jump landings in parallel and in turn-out (specifically 1st position). Three-dimensional ankle mechanics, landing vGRF variables, and jump height were recorded via a seven-camera motion capture system and one force platform. As above, Intraclass class correlation coefficients and coefficients of variation are used to establish the reliability and variability of outcome measures. Unlike the previous chapter, all participants included were professional ballet dancers.

2.10.3 Section 3: Jumping and Landing in Ballet

Chapters 7 and 8 build on the rationale of Section 1 and the methods of Section 2 to investigate jumping and landing in professional ballet dancers.

2.10.3.1 Chapter 7: Ankle Mechanics During Jump Landings Across Different Foot Positions in Professional Ballet Dancers

How do sex and foot position influence ankle mechanics and vGRF during jump landings in professional ballet dancers?

Chapter 7 aimed to investigate the association of sex and foot position on ankle joint mechanics and vGRF during jump landings in professional ballet dancers.

Twenty-seven participants completed five countermovement jumps across seven different foot positions (parallel, first, second, fourth front, fourth back, fifth front, and fifth back). Linear discriminant analyses were used to investigate significant main effects following a repeated measures MANOVA.

2.10.3.2 Chapter 8: Strength, Range of Motion, and Dynamic Joint Alignment are Poorly Associated with Ankle Mechanics and Ground Reaction Forces During Jump Landings in Professional Ballet Dancers

Can the load experienced at the ankle joint and system level be predicted from ROM, dynamic alignment, and lower limb strength?

Chapter 8 investigates the potential moderators of load in professional ballet dancers, including static dorsiflexion ROM, three-dimensional ankle excursions, and lower extremity isometric strength. Two linear mixed-effects models were used to investigate the association between the predictor variables and the outcome variables. All predictor variables were entered as fixed effects and foot position, sex, and unique dancer identification were entered as random effects. Model fit, coefficient estimates (effect size), and *p* values are used to collectively interpret associations which are then discussed.

2.10.4 General Discussion

This final chapter summarises the overall findings of the present thesis in the context of the wider research landscape and current best practices within applied environments.

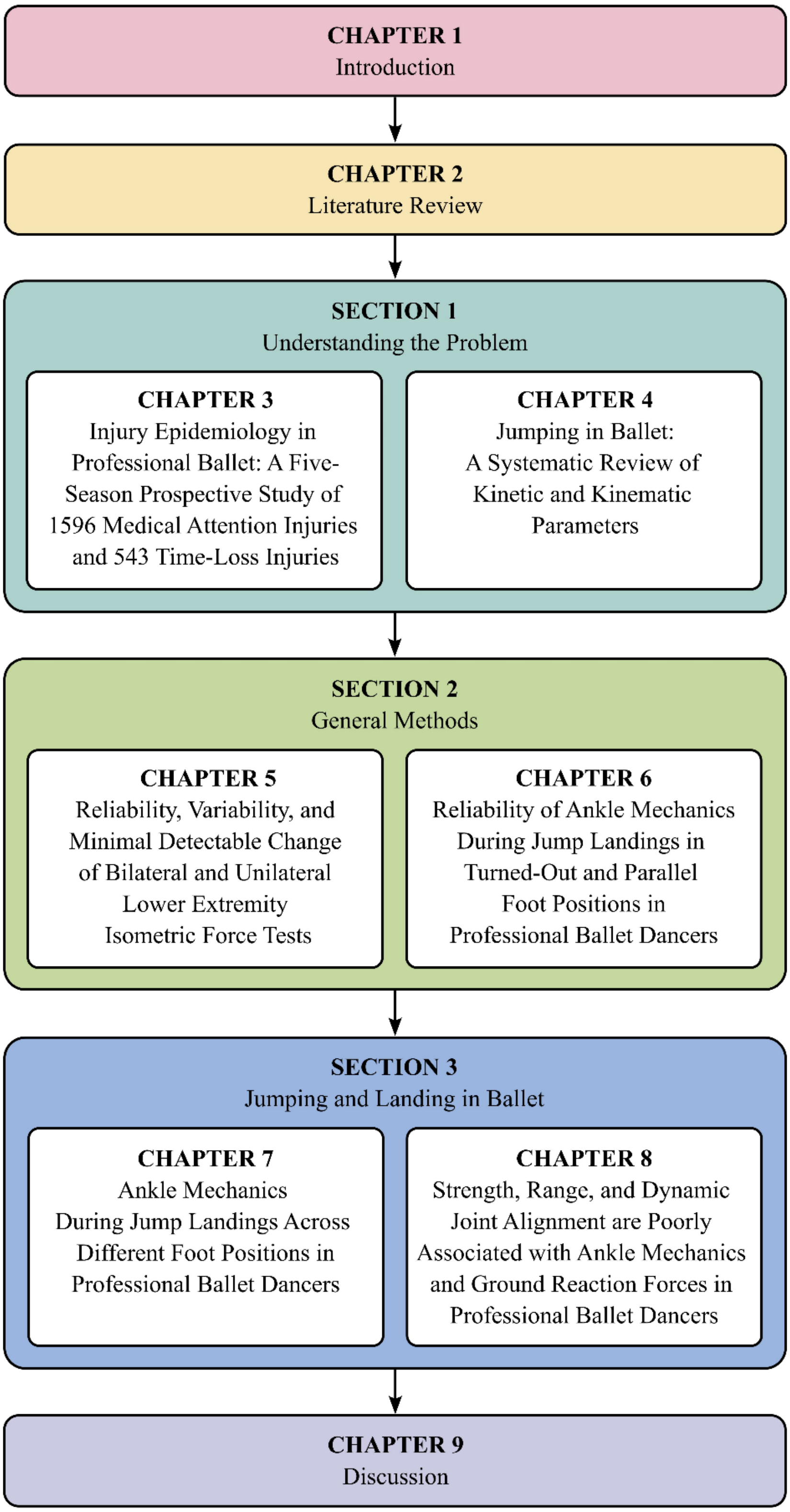


Figure 2.8 A visual overview of the structure of the present thesis.

SECTION 1: UNDERSTANDING THE PROBLEM

CHAPTER 3

Injury Epidemiology in Professional Ballet: A Five-Season Prospective Study of 1596 Medical Attention Injuries and 543 Time-Loss Injuries

3.1 Abstract

Objective To describe the incidence rate, severity, burden, and aetiology of medical attention and time-loss injuries across five consecutive seasons at a professional ballet company.

Methods Medical attention injuries, time-loss injuries, and dance exposure hours of 123 professional ballet dancers (female: $n = 66$, age: 28.0 ± 8.3 y; male: $n = 57$, age: 27.9 ± 8.5 y) were prospectively recorded between the 2015/16 and 2019/20 seasons.

Results The incidence rate (per 1000 h) of medical attention injury was 3.9 (95% CI: 3.3–4.4) for women and 3.1 (95% CI: 2.6–3.5) for men. The incidence rate (per 1000 h) of time-loss injury was 1.2 (95% CI: 1.0–1.5) for women and 1.1 (95% CI: 0.9–1.3) for men. First Soloists and Principals experienced between 2.0–2.2 additional medical attention injuries per 1000 hours and 0.9–1.1 additional time-loss injuries per 1000 hours compared with Apprentices ($p \leq .025$). Further, intra-season differences were observed in medical attention, but not time-loss, injury incidence rates with the highest incidence rates in early (August and September) and late (June) season months. Thirty-five percent of time-loss injuries resulted in over 28 days of modified dance training. A greater percentage of time-loss injuries were classified as overuse (female: 50%; male: 51%) compared with traumatic (female: 40%; male: 41%).

Conclusion This is the first study to report the incidence rate of medical attention and time-loss injuries in professional ballet dancers. Incidence rates differed across company ranks and months, which may inform targeted injury prevention strategies.

3.2 Introduction

The probability of sustaining a musculoskeletal injury in professional ballet is high, with one article reporting an incidence proportion of 6.8 injuries per dancer over a season.[4] However, differences in time-loss injury are observed across professional ballet companies, with incidence proportions ranging from 1.8–6.8 injuries per dancer.[4,15,16,46,84–86] Similarly, differences in incidence rates are observed across studies, with values ranging from 0.6–4.4 injuries per 1000 hours of dance exposure.[4,46,84,86] The variation in incidence rates may reflect the use of contractual hours when calculating dance exposure (as opposed to individualised class, rehearsal, and performance schedules) or inconsistent injury definitions across studies.[15,16,84–86]

No research has described the incidence rate of medical attention injuries In professional ballet. The inclusion of medical attention injuries in epidemiology research has been recommended by Clarsen and Bahr,[40] and various consensus statements in sport,[30,31] as it provides a more comprehensive understanding of the medical burden within an organization. Medical attention injuries, for example, impact performance outcomes in professional cricket.[188] Although performance outcomes in professional ballet are less tangible than sport, medical attention injury incidence rates may affect casting. Quantifying the incidence rate of medical attention injuries alongside time-loss injuries is therefore an important step towards effective medical management within professional ballet.[17]

Most injury epidemiology research in professional ballet is not reported in line with current methodological standards and lacks comprehensive contextual detail.[8] For example, atypical or no severity scales have been applied, there is inconsistent reporting of injury definitions, diagnoses, and tissue types, and few studies have reported differences in injury incidence rates and aetiology across contextual risk factors.[4,15,16,46,84–86] Specific injury risk factors, such as sex, company rank, and intra- and inter-season variation, have been identified in professional ballet.[189,190] However, only one study has reported statistical differences in injury incidence rates across sex and rank,[4] and although several studies have reported longitudinal injury incidence rates in professional ballet dancers,[15,16,46,84,86] none of these conduct statistical analyses.

This study aimed to investigate the sex, company rank, and intra- and inter-season differences in medical attention and time-loss injury incidence rates across five consecutive seasons at a professional ballet company. We also aimed to describe the severity, burden, and aetiology of medical attention and time-loss injuries.

3.3 Methods

3.3.1 Study Design and Setting

A prospective cohort study design was employed to investigate medical attention and time-loss injuries in professional ballet dancers. Data were collected across five consecutive seasons at The Royal Ballet, commencing August 8th 2015 and ending March 15th 2020. The 2019/20 season ended prematurely due to the COVID-19 global pandemic. All scheduled dance events were completed within the Royal Opera House, London. All dance exposure and medical data were entered into standardised electronic forms (Smartabase version 6.5.11, Fusion Sport, Brisbane, Australia). Medical attention and time-loss injuries were evaluated and recorded by in-house Chartered Physiotherapists, typically within 24 hours of the onset. Dance exposure data were prospectively entered by the company's Artistic Scheduling Manager. Injury diagnoses were categorised using version 10 of the Orchard Sports Injury Classification System (OSICS).[191] Data entered outside of each season were excluded from the analysis (e.g., tour, summer break). There was no patient or public involvement in the design, conduct, or reporting of this study.

3.3.2 Participants

Of 124 eligible elite professional dancers across the ranks of Apprentice, Artist, First Artist, Soloist, First Soloist, Principal, and Principal Character Artist, 123 were included in this analysis (female: 66, age: 28.0 ± 8.3 y; male: 57, age: 27.9 ± 8.5 y; Figure 3.1). Dancers who joined or left the company during the study period were included for the duration of their time in the company. Written informed consent was provided by 108 dancers. The remaining 16 were contacted, one of which declined consent, and 15 did not respond. A legitimate interest assessment to use the anonymised data for the present analysis was approved by the Data Controller of the Royal Opera House, in line with GDPR (2016) and the UK Data Protection Act (2018).

Written support was provided by the Clinical Director of The Royal Ballet. Ethical approval was granted by St Mary's University Ethics Committee in accordance with the Declaration of Helsinki (Appendix B).

3.3.3 Injury Definitions

Medical attention injuries were defined as "any musculoskeletal complaint that required medical attention from a physiotherapist".[40] Time-loss injuries were defined as "any injury that prevented a dancer from taking a full part in all dance-related activities that would normally be required of them for a period equal to or greater than 24 hours after the injury was sustained".[4] Time-loss injuries were closed on the date of their final appointment when no follow-up appointment occurred within 28 days. Prevalence was defined as the count of injured dancers divided by the count of included dancers each season. Incidence proportion was defined as the count of injuries divided by the count of included dancers each season. Severity was classified as either minor (1–7 days), moderate (8–28 days), or severe (>28 days).[192] Recurrent injury was defined as "any injury of the same location and type as the index injury, which occurred following a full return to all dance-related activities".[193] Overuse injuries were defined as "any medical incident that did not have a sudden onset from a discrete event".[194] The nature of injuries was categorised based on the physiotherapist's interpretation of the primary risk factor, where intrinsic was related to the characteristics of the individual and extrinsic was related to environmental factors.[2] The term "not classified" was applied when a physiotherapist was unable to distinguish the mechanism, activity, footwear, classification, occurrence, or nature of the injury.

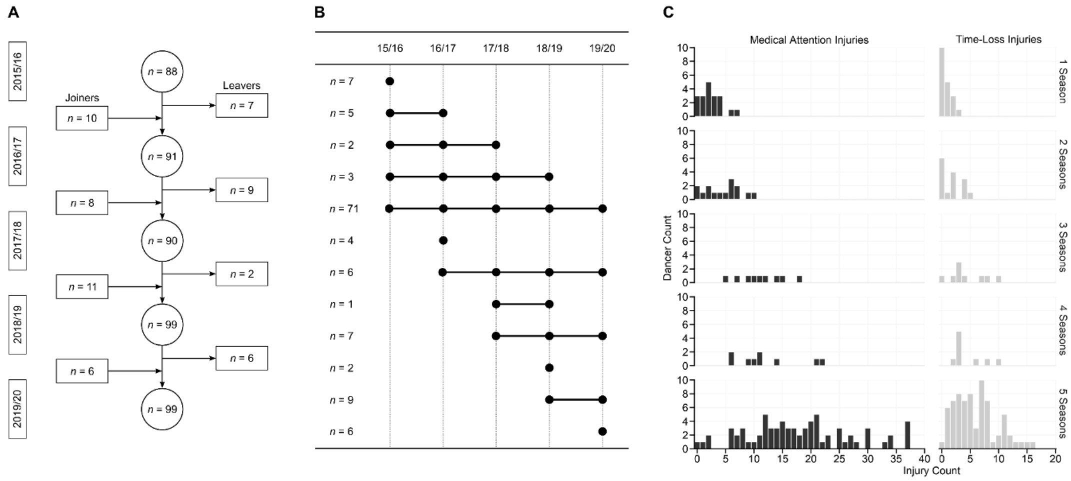


Figure 3.1 A) The number of participants joining, leaving, and present each season. B) The number of participants who were present across specific seasons. C) The count of injuries across participants who were involved in one, two, three, four, or five seasons.

3.3.4 Data Analysis

3.3.4.1 Dance Exposure

Individualised exposure hours for class, rehearsal, and performance were extracted from the online data management system and calculated for each dancer. Performance casts for each show were inspected manually and cross-referenced with updated casting sheets to account for cast changes. Following a new time-loss injury, prospectively scheduled dance events were removed to accurately calculate dance exposure. Individualised rehearsal and performance exposure hours were grouped by production length (i.e., stand-alone full-length ballets (≥ 90 minutes) or shorter productions that were staged together (< 90 minutes)), and by production type (i.e., new creations or existing works).

3.3.4.2 Medical Attention and Time-Loss Injury

The total medical attention injuries, time-loss injuries, and exposure hours were calculated for each unique dancer and grouped by sex, rank, month, season. The incidence rate (per 1000 h) of medical attention and time-loss injuries by production length, production type, anatomical region, and tissue type was calculated by dividing grouped injury count by grouped exposure time. Mean prevalence and incidence proportion of medical attention and time-loss injuries were calculated across the four complete seasons (2015/16–2018/19). Time-loss injury severity was calculated as median days lost, as severity data were not normally distributed. Time-loss injury severity was also calculated as the percentage of injuries classed as minor, moderate, and severe. Injury burden (days lost per 1000 h) and risk matrices (incidence rate × median severity) were calculated by anatomical region and tissue type. The number and percentage of medical attention and time-loss injuries by activity, mechanism, footwear, occurrence, classification, nature was calculated. For all values, 95% confidence intervals (CI) were calculated. Mechanism of injury fields were concatenated based on movement similarities (e.g., '*Plié*' and '*Relevé*' became '*Plié/relevé*'). The anatomical region and tissue type of injuries were classified using the OSICS diagnosis code.[8,191] There were five open injury records at the onset of the study. Three dancers were partaking in restricted rehearsals, and were therefore included in the study from the onset. Two were fully removed from normal rehearsal, but returned to rehearsal after 34 and 55 days; these dancers were included in the study following their return.

3.3.5 Statistical Analysis

A Poisson generalized linear mixed model was used to calculate incidence rates for all medical attention and time-loss injuries using the *lme4* package.[195] The output variable was the number of recorded medical attention and time-loss injuries offset by the log of dance exposure hours for each individual. Sex, rank, sex × rank interaction, month, and season were included as fixed factors. Dancer identity was included as a random factor to account for repeated observations over time. Main effects of the generalized linear mixed model were compared by applying an analysis of variance using the *car* package.[196] The estimated marginal means (EMM) for each fixed factor were extracted from the model, with 95% CI, and back-transformed to calculate incidence rate per 1000 hours using the *emmeans* package.[197] Post-hoc pairwise comparisons, with false discovery rate adjustment, were used to investigate statistically significant main effects.[197] Significance was set at $p \leq .025$ to account for two primary outcome measures. All data and statistical analysis were conducted using *R* (version 4.0.3, R Foundation for Statistical Computing, Vienna, Austria).

3.4 Results

3.4.1 Dance Exposure

There were 20,762 unique scheduled dance events over 5 consecutive seasons. This resulted in 283,453 individual dancer events (class: 99,733; rehearsal: 152,588; performance: 31,132). Scheduled dance events represented a total of 417,693 hours of individual dance exposure (class: 115,772; rehearsal: 209,529; performance: 92,392).

3.4.2 Injuries

Table 3.1 outlines the number of dancers, medical attention injuries, and time-loss injuries over the five seasons. The count of injuries by dancer and number of seasons in the company is presented in Figure 3.1.

3.4.3 Incidence Rates by Sex and Company Rank

The incidence rates of medical attention and time-loss injuries can be found in Table 3.2. A significant main effect of company rank was observed on medical attention injury incidence rate ($F_7 = 2209.1$; $p < .001$). Post-hoc pairwise comparisons revealed that medical attention incidence rates were lower in Apprentices (2.5 per 1000 h; 95% CI: 1.9–3.2) than First Soloists (4.5 per 1000 h; 95% CI: 3.7–5.5; $p = .003$), and Principals (4.7 per 1000 h; 95% CI: 3.9–5.8; $p = .002$). No significant main effects of sex ($p = .031$) or sex × rank ($p = .659$) were observed on medical attention incidence rate.

A significant main effect of company rank was observed on time-loss injury incidence rate ($F_7 = 1216.2$; $p < .001$). Post-hoc pairwise comparisons revealed that Apprentices (0.6 per 1000 h; 95% CI: 0.4–1.0) demonstrated lower time-loss injury incidence rates than First Soloists (1.5 per 1000 h; 95% CI: 1.1–2.1; $p = .015$) and Principals (1.7 per 1000 h; 95% CI: 1.3–2.4; $p = .006$). No significant main effects of sex ($p = .496$) or sex × rank ($p = .205$) were observed on time-loss injury incidence rate.

Table 3.1 Number of dancers, medical attention injuries, and time-loss injuries across five consecutive seasons.

	2015/16			**2016/17**			**2017/18**			**2018/19**			**2019/20**		
	n	**MA**	**TL**	***n***	**MA**	**TL**	***n***	**MA**	**TL**	***n***	**MA**	**TL**	***n***	**MA**	**TL**
All	88	384	88	91	305	112	90	338	138	99	286	130	99	283	75
Female	48	228	53	50	180	60	49	183	75	52	171	70	53	163	42
App.	2	8	1	4	10	4	3	4	2	4	5	1	4	12	2
Artist	11	46	8	11	46	11	10	53	21	14	53	17	12	33	7
F. Artist	9	35	12	10	31	11	11	43	26	10	28	10	12	48	16
Soloist	11	62	21	9	27	10	8	30	7	4	11	3	5	15	3
F. Soloist	7	39	5	7	33	12	6	18	4	9	37	21	9	31	3
Principal	6	36	6	8	31	10	8	30	12	8	29	13	8	16	8
PCA	2	2	0	1	2	2	3	5	3	3	8	5	3	8	3
Male	40	156	35	41	125	52	41	155	63	47	115	60	46	120	33
App.	3	6	0	4	9	2	4	18	9	4	4	1	2	4	0
Artist	7	30	5	7	26	9	7	23	11	10	30	15	11	36	11
F. Artist	5	21	5	6	20	4	6	22	5	7	14	8	7	24	5
Soloist	8	27	7	7	21	13	7	39	14	7	26	15	8	15	4
F. Soloist	7	29	6	5	20	9	4	20	11	5	14	9	5	14	4
Principal	7	42	12	9	27	13	8	23	8	9	20	8	8	23	6
PCA	3	1	0	3	2	2	5	10	5	5	7	4	5	4	3

App., Apprentice; F. Artist, First Artist; F. Soloist, First Soloist; PCA, Principal Character Artist; MA, Medical Attention Injury; TL Time-Loss Injury

3.4.4 Intra- and Inter-Season Incidence Rates

A significant main effect of month ($F_{10} = 59.7$; $p < .001$) and season ($F_4 = 31.9$; $p < .001$) was observed on medical attention injury incidence rate (per 1000 h); post-hoc pairwise comparisons are illustrated in Figure 4.2. No main effects of month ($p = .029$) or season ($p = .042$) were observed on time-loss injury incidence rate.

3.4.5 Incidence Rates by Production Type

Medical attention and time-loss injury incidence rates were 6.0 (95% CI: 5.5–6.6) and 2.0 (95% CI: 1.7–2.3) per 1000 hours for mixed bills and 3.7 (95% CI: 3.4–4.0) and 1.2 (95% CI: 1.1–1.4) per 1000 hours for full-length productions, respectively. Medical attention and time-loss injury incidence rates were 4.2 (95% CI: 3.6–4.8) and 1.5 (95% CI: 1.2–1.9) per 1000 hours for new creations and 4.3 (95% CI: 4.0–4.6) and 1.4 (95% CI: 1.3–1.6) per 1000 hours for existing productions, respectively.

3.4.6 Prevalence and Incidence Proportion

Table 3.2 outlines the mean prevalence and incidence proportion of medical attention and time-loss injuries across the four complete seasons (2015/16–2018/19).

Table 3.2 Estimated marginal mean incidence rate (per 1000 h), prevalence (% injured dancers), incidence proportion (injuries per dancer) of medical attention and time-loss injuries across five consecutive seasons (95% confidence intervals).

	Medical Attention Injury						**Time-Loss Injury**					
	Incidence Rate		**Prevalence***		**Incidence Proportion***		**Incidence Rate**		**Prevalence***		**Incidence Proportion***	
	Female	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**
All Ranks	3.9 [3.3, 4.4]	3.1 [2.6, 3.5]	91.5 [82.0, 100.0]	88.4 [78.5, 98.2]	3.8 [3.7, 4.0]	3.3 [3.0, 3.6]	1.2 [1.0, 1.5]	1.1 [0.9, 1.3]	70.3 [60.8, 79.9]	61.4 [51.6, 71.3]	1.3 [1.1, 1.5]	1.2 [1, 1.5]
App.	2.7 [1.9, 3.8]	2.3 [1.6, 3.3]	79.2 [57.6, 100.0]	87.5 [56.7, 100.0]	2.3 [2.0, 2.6]	2.4 [1.4, 3.4]	0.6 [0.3, 1.3]	0.6 [0.3, 1.1]	45.8 [24.2, 67.4]	31.2 [0.4, 62.1]	0.6 [0.3, 0.9]	0.8 [0.0, 1.8]
Artist	3.4 [2.8, 4.2]	3.1 [2.5, 3.9]	94.2 [79.2, 100.0]	93.9 [70.7, 100.0]	4.4 [3.8, 4.9]	3.6 [3.2, 4.0]	0.9 [0.6, 1.3]	1.0 [0.7, 1.5]	68.1 [53.2, 83.1]	73.6 [50.3, 96.8]	1.3 [0.7, 1.8]	1.3 [0.9, 1.6]
F. Artist	4.2 [3.4, 5.3]	2.8 [2.1, 3.7]	92.2 [73.9, 100.0]	88.7 [77.0, 100.0]	3.4 [2.8, 4.0]	3.3 [3.1, 3.5]	1.5 [1.1, 2.2]	0.7 [0.4, 1.1]	76.4 [58.1, 94.7]	50.1 [38.4, 61.8]	1.4 [0.8, 2.1]	0.9 [0.7, 1.1]
Soloist	4.1 [3.2, 5.2]	3.2 [2.5, 4.2]	85.1 [66.8, 100.0]	90.2 [70.1, 100.0]	3.8 [3.3, 4.3]	3.9 [3.4, 4.5]	1.4 [0.9, 2.1]	1.3 [0.9, 1.9]	68.7 [50.4, 87.0]	66.5 [46.4, 86.6]	1.2 [0.7, 1.7]	1.7 [1.2, 2.3]
F. Soloist	5.3 [4.1, 6.9]	3.8 [2.8, 5.2]	93.7 [72.9, 100.0]	100.0 [88.1, 100.0]	4.3 [3.6, 5.1]	4.0 [3.2, 4.7]	1.5 [0.9, 2.2]	1.6 [1.0, 2.6]	71.0 [50.3, 91.8]	82.9 [71.0, 94.7]	1.4 [0.6, 2.2]	1.8 [1.0, 2.6]
Principal	4.8 [3.5, 6.4]	4.7 [3.6, 6.3]	100.0 [91.6, 100.0]	96.9 [87.3, 100.0]	4.3 [4.0, 4.6]	3.5 [3.1, 3.9]	1.7 [1.1, 2.6]	1.8 [1.2, 2.8]	76.0 [67.6, 84.5]	66.8 [57.2, 76.4]	1.3 [1.1, 1.6]	1.3 [0.9, 1.6]
PCA	3.2 [1.8, 5.5]	2.1 [1.3, 3.5]	87.5 [46.4, 100.0]	45.0 [18.1, 71.9]	1.8 [1.0, 2.7]	1.1 [0.7, 1.5]	1.6 [0.7, 3.6]	1.1 [0.5, 2.1]	58.3 [17.2, 99.4]	36.7 [9.7, 63.6]	1.2 [0.3, 2.0]	0.6 [0.2, 1.0]

App., Apprentice; F. Artist, First Artist; F. Soloist, First Soloist; PCA, Principal Character Artist; MA, Medical Attention Injury; TL, Time-Loss Injury; * calculated based on four seasons of data due to the premature end of the 2019/20 season.

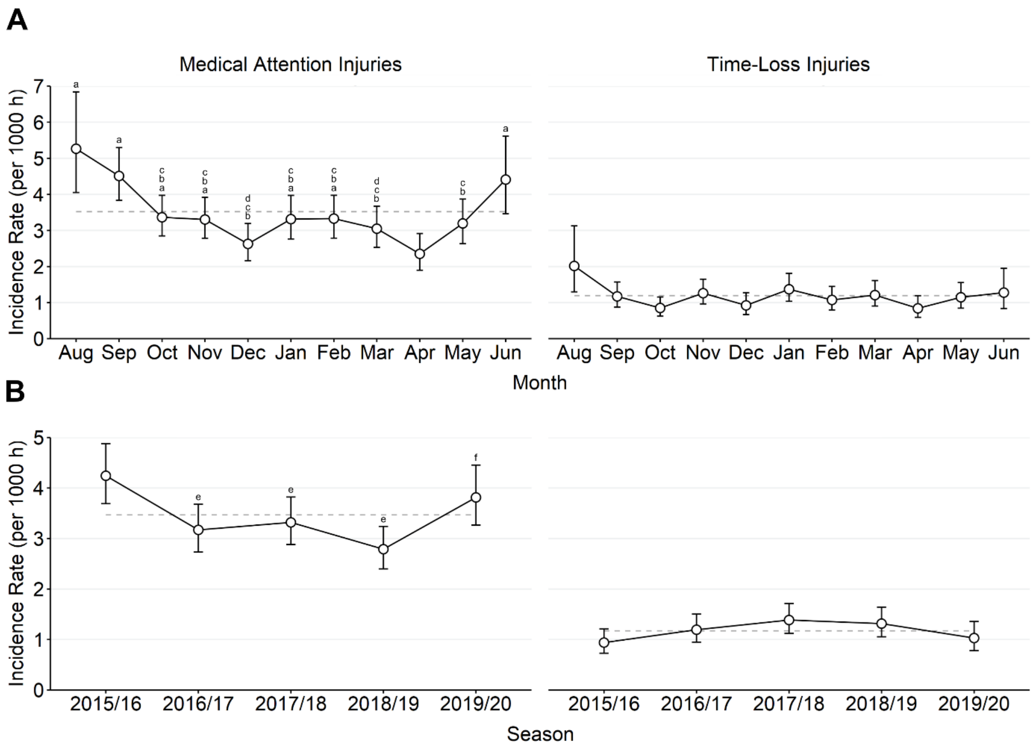


Figure 3.2 A) Intra-season medical attention and time-loss injury incidence rate with 95% CI. ^{a} Significantly different to April ($p < .025$); ^{b} Significantly different to August ($p < 0.025$); ^{c} Significantly different to September ($p < .025$); ^{d} Significantly different to June ($p < .025$). B) Inter-season medical attention and time-loss injury incidence rate with 95% CI. ^{e} Significantly different to the 2015/16 season ($p < .025$); ^{f} Significantly different to the 2018/19 season ($p < .025$).

3.4.7 Severity, Burden, and Aetiology of Injuries

Table 3.3 presents the median severity and percentage of time-loss injuries by severity scale. Figure 3.3 illustrates the time-loss injury burden by anatomical region and tissue type. The incidence rate, severity, and burden of time-loss injuries by anatomical region and tissue type are presented in Table 3.4. Table 3.5 outlines the percentage of medical attention and time-loss injuries by classification, occurrence, and nature. The percentage of medical attention and time-loss injuries by mechanism, activity, and footwear is provided in Table 3.6.

Table 3.3 Median severity of time-loss injuries and percentage of time-loss injuries by severity scale (95% confidence intervals)

	Female	**Male**
Median Severity (days)		
All Ranks	14 (10–16)	14 [7, 16]
App.	17 [2, 123]	22 (10–39)
Artist	10 [3, 16]	12 (6–31)
F. Artist	24 [11, 30]	14 (3–18)
Soloist	9 [3, 33]	12 (3–18)
F. Soloist	18 [8, 25]	21 (8–41)
Principal	9 [4, 16]	6 (2–27)
PCA	10 [1, 14]	14 (6–25)
Severity Scale (%)		
Mild (1–7 days)	39.9 (24.7–55.1)	41.5 [26.5, 56.5]
Moderate (8–28)	25.2 (8.2–42.1)	23.7 [6.5, 40.8]
Severe (>28)	34.9 (19.1–50.7)	34.9 [19.0, 50.7]

App., Apprentice; F. Artist, First Artist; F. Soloist, First Soloist; PCA, Principal Character Artist

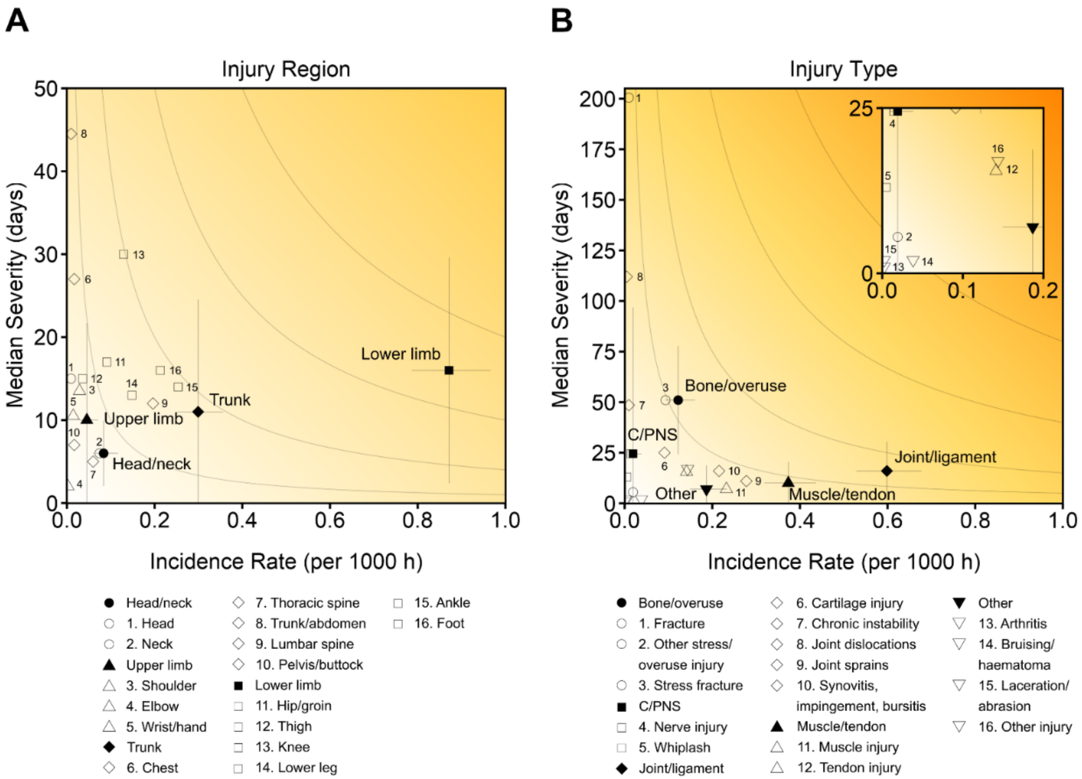


Figure 3.3 A) Time-loss injury burden (incidence rate × median severity) by anatomical region with 95% CI. B) Time-loss injury burden (incidence rate × median severity) by tissue type with 95% CI. The top right corner of plot B depicts a zoomed-in subsection of the main plot identifiable by the axis. It should be noted that the y-axis scale across plot A and B are not equal.

Table 3.4 Number of injuries, incidence rate (injuries per 1000 h), severity (median days lost), and burden (days lost per 1000 h) of time-loss injuries by injury region and tissue type (95% confidence intervals).

	***n* injuries**		**Incidence Rates**		**Severity**		**Burden**	
	Female	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**
Head	2	2	0.01 [0.00, 0.04]	0.01 [0.00, 0.04]	15 [0, 33]	15 [0, 40]	0 [0, 1]	0 [0, 1]
Neck	17	14	0.08 [0.05, 0.12]	0.07 [0.04, 0.12]	4 [0, 9]	6 [0, 13]	1 [0, 1]	1 [0, 1]
Shoulder	3	9	0.01 [0.00, 0.04]	0.05 [0.02, 0.09]	7 [0, 48]	17 [2, 32]	0 [0, 1]	1 [1, 2]
Elbow	1	-	0.00 [0.00, 0.03]	-	2 [0, 0]	-	0 [0, 0]	-
Wrist/hand	1	5	0.00 [0.00, 0.03]	0.03 [0.01, 0.06]	14 [0, 0]	7 [0, 33]	0 [0, 0]	0 [0, 1]
Chest	4	3	0.02 [0.01, 0.05]	0.02 [0.00, 0.05]	18 [0, 106]	27 [0, 76]	1 [0, 2]	1 [0, 2]
Thoracic spine	10	15	0.04 [0.02, 0.08]	0.08 [0.05, 0.13]	10 [0, 24]	4 [0, 32]	1 [0, 2]	2 [1, 3]
Trunk/abdomen	4	-	0.02 [0.01, 0.05]	-	44 [0, 101]	-	1 [0, 3]	-
Lumbar spine	48	34	0.22 [0.16, 0.29]	0.17 [0.12, 0.24]	16 [2, 31]	5 [0, 37]	6 [5, 9]	6 [4, 9]
Joint sprains	5	5	0.02 [0.01, 0.05]	0.03 [0.01, 0.06]	39 [0, 100]	6 [0, 39]	1 [1, 4]	1 [0, 1]
Cartilage injury	11	5	0.05 [0.03, 0.09]	0.03 [0.01, 0.06]	20 [0, 51]	27 [8, 46]	2 [1, 3]	1 [0, 1]
Synovitis, impingement, bursitis	14	11	0.06 [0.04, 0.11]	0.06 [0.03, 0.10]	12 [3, 21]	2 [0, 32]	1 [1, 2]	1 [1, 2]
Muscle injury	10	8	0.04 [0.02, 0.08]	0.04 [0.02, 0.08]	12 [0, 34]	2 [0, 21]	1 [1, 2]	1 [0, 1]
Pelvis/buttock	6	1	0.03 [0.01, 0.06]	0.01 [0.00, 0.04]	9 [0, 59]	1 [0, 0]	1 [0, 2]	0 [0, 0]
Hip/groin	26	12	0.12 [0.08, 0.17]	0.06 [0.03, 0.11]	23 [0, 56]	10 [0, 24]	6 [4, 8]	1 [1, 2]
Synovitis, impingement, bursitis	8	4	0.04 [0.02, 0.07]	0.02 [0.01, 0.05]	27 [0, 114]	15 [2, 28]	2 [1, 5]	0 [0, 1]
Other injury	7	3	0.03 [0.01, 0.07]	0.02 [0.00, 0.05]	33 [0, 92]	52 [21, 83]	2 [1, 4]	1 [0, 2]
Thigh	5	10	0.02 [0.01, 0.05]	0.05 [0.03, 0.10]	6 [0, 19]	16 [0, 38]	0 [0, 1]	1 [1, 2]
Knee	25	29	0.11 [0.08, 0.17]	0.15 [0.10, 0.21]	21 [0, 64]	32 [0, 72]	7 [5, 11]	9 [6, 13]
Joint sprains	5	3	0.02 [0.01, 0.05]	0.02 [0.00, 0.05]	119 [0, 256]	17 [0, 308]	3 [1, 6]	2 [1, 8]
Tendon injury	2	12	0.01 [0.00, 0.04]	0.06 [0.03, 0.11]	80 [55, 105]	25 [0, 64]	1 [0, 3]	3 [1, 5]
Lower leg	32	30	0.14 [0.10, 0.20]	0.15 [0.11, 0.22]	7 [0, 25]	18 [0, 48]	4 [3, 5]	7 [5, 10]
Stress fracture	8	7	0.04 [0.02, 0.07]	0.04 [0.02, 0.08]	60 [23, 96]	71 [0, 143]	2 [1, 4]	3 [2, 7]
Muscle injury	16	19	0.07 [0.04, 0.12]	0.10 [0.06, 0.15]	7 [0, 32]	14 [6, 22]	2 [1, 2]	2 [1, 2]
Ankle	66	40	0.30 [0.23, 0.38]	0.21 [0.15, 0.28]	14 [0, 42]	12 [0, 35]	13 [10, 17]	8 [6, 11]
Joint sprains	21	6	0.09 [0.06, 0.14]	0.03 [0.01, 0.07]	14 [0, 38]	14 [0, 58]	3 [2, 5]	1 [1, 3]
Synovitis, impingement, bursitis	20	14	0.09 [0.06, 0.14]	0.07 [0.04, 0.12]	22 [0, 85]	10 [0, 46]	5 [3, 8]	3 [2, 4]
Tendon injury	19	14	0.09 [0.05, 0.13]	0.07 [0.04, 0.12]	7 [0, 43]	11 [0, 36]	3 [2, 5]	2 [1, 3]
Foot	50	39	0.22 [0.17, 0.30]	0.20 [0.15, 0.27]	16 [0, 34]	16 [0, 45]	8 [6, 11]	9 [7, 13]
Stress fracture	13	9	0.06 [0.03, 0.10]	0.05 [0.02, 0.09]	46 [16, 76]	46 [0, 110]	3 [2, 5]	3 [2, 7]
Joint sprains	19	8	0.09 [0.05, 0.13]	0.04 [0.02, 0.08]	14 [1, 27]	27 [5, 49]	2 [1, 3]	1 [1, 3]

Table 3.5 Number and percentage of medical attention and time-loss injuries by classification, occurrence, and nature (95% confidence intervals).

	Medical Attention Injury				**Time-Loss Injury**			
	***n* injuries**		**Percentage**		***n* injuries**		**Percentage**	
	Female	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**
Classification								
Overuse	637	434	68.9 [65.9, 71.8]	64.7 [61.1, 68.3]	151	125	50.3 [44.7, 56.0]	51.4 [45.2, 57.7]
Traumatic	223	185	24.1 [21.4, 26.9]	27.6 [24.2, 31.0]	121	99	40.3 [34.8, 45.9]	40.7 [34.6, 46.9]
Not classified	65	52	7.0 [5.4, 8.7]	7.7 [5.7, 9.8]	28	19	9.3 [6.0, 12.6]	7.8 [4.4, 11.2]
Occurrence								
First episode	597	427	64.5 [61.5, 67.6]	63.6 [60.0, 67.3]	213	162	71.0 [65.9, 76.1]	66.7 [60.7, 72.6]
Recurrence	321	237	34.7 [31.6, 37.8]	35.3 [31.7, 38.9]	85	79	28.3 [23.2, 33.4]	32.5 [26.6, 38.4]
Not classified	7	7	0.8 [0.2, 1.3]	1.0 [0.3, 1.8]	2	2	0.7 [0.0, 1.6]	0.8 [0.0, 2.0]
Nature								
Extrinsic	249	174	26.9 [24.1, 29.8]	25.9 [22.6, 29.2]	99	80	33.0 [27.7, 38.3]	32.9 [27.0, 38.8]
Intrinsic	670	493	72.4 [69.6, 75.3]	73.5 [70.1, 76.8]	199	162	66.3 [61.0, 71.7]	66.7 [60.7, 72.6]
Not classified	6	4	0.6 [0.1, 1.2]	0.6 [0.0, 1.2]	2	1	0.7 [0.0, 1.6]	0.4 [0.0, 1.2]

Table 3.6 Number and percentage of medical attention and time-loss injuries by injury mechanism, activity, and footwear (95% confidence intervals).

	Medical Attention Injury				**Time-Loss Injuries**			
	***n* injuries**		**Percentage**		***n* injuries**		**Percentage**	
	Female	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**
Mechanism								
Jumping/landing	200	206	21.6 [19.0, 24.3]	30.7 [27.2, 34.2]	81	92	27.0 [22.0, 32.0]	37.9 [31.8, 44.0]
Pointe	132	3	14.3 [12.0, 16.5]	0.4 [0.0, 1.0]	37	0	12.3 [8.6, 16.1]	0.0 [0.0, 0.0]
Plié/relevé	66	64	7.1 [5.5, 8.8]	9.5 [7.3, 11.8]	21	21	7.0 [4.1, 9.9]	8.6 [5.1, 12.2]
Lifting/lifted	31	98	3.4 [2.2, 4.5]	14.6 [11.9, 17.3]	11	29	3.7 [1.5, 5.8]	11.9 [7.9, 16.0]
Arabesque	65	20	7.0 [5.4, 8.7]	3.0 [1.7, 4.3]	15	7	5.0 [2.5, 7.5]	2.9 [0.8, 5.0]
Pirouette	11	20	1.2 [0.5, 1.9]	3.0 [1.7, 4.3]	2	8	0.7 [0.0, 1.6]	3.3 [1.0, 5.5]
Non-dance related	60	36	6.5 [4.9, 8.1]	5.4 [3.7, 7.1]	25	14	8.3 [5.2, 11.5]	5.8 [2.8, 8.7]
Cannot recall	89	60	9.6 [7.7, 11.5]	8.9 [6.8, 11.1]	33	18	11.0 [7.5, 14.5]	7.4 [4.1, 10.7]
Not classified	271	164	29.3 [26.4, 32.2]	24.4 [21.2, 27.7]	75	54	25.0 [20.1, 29.9]	22.2 [17.0, 27.4]
Activity								
Rehearsal	478	307	51.7 [48.5, 54.9]	45.8 [42.0, 49.5]	149	100	49.7 [44.0, 55.3]	41.2 [35.0, 47.3]
Performance	206	110	22.3 [19.6, 25.0]	16.4 [13.6, 19.2]	66	45	22.0 [17.3, 26.7]	18.5 [13.6, 23.4]
Class	104	140	11.2 [9.2, 13.3]	20.9 [17.8, 23.9]	34	49	11.3 [7.7, 14.9]	20.2 [15.1, 25.2]
Gym	8	21	0.9 [0.3, 1.5]	3.1 [1.8, 4.4]	1	7	0.3 [0.0, 1.0]	2.9 [0.8, 5.0]
Pilates/Gyrotonics®	3	1	0.3 [0.0, 0.7]	0.1 [0.0, 0.4]	1	0	0.3 [0.0, 1.0]	0.0 [0.0, 0.0]
Rehab	-	3	-	0.4 [0.0, 1.0]	-	2	-	0.8 [0.0, 2.0]
Non-dance related	56	39	6.1 [4.5, 7.6]	5.8 [4.0, 7.6]	25	20	8.3 [5.2, 11.5]	8.2 [4.8, 11.7]
Not classified	70	50	7.6 [5.9, 9.3]	7.5 [5.5, 9.4]	24	20	8.0 [4.9, 11.1]	8.2 [4.8, 11.7]
Footwear								
Ballet Flats	106	533	11.5 [9.4, 13.5]	79.4 [76.4, 82.5]	34	187	11.3 [7.7, 14.9]	77.0 [71.7, 82.2]
Pointe Shoes	658	7	71.1 [68.2, 74.1]	1.0 [0.3, 1.8]	210	2	70.0 [64.8, 75.2]	0.8 [0.0, 2.0]
Character Shoes	30	22	3.2 [2.1, 4.4]	3.3 [1.9, 4.6]	9	10	3.0 [1.1, 4.9]	4.1 [1.6, 6.6]
Barefoot	8	9	0.9 [0.3, 1.5]	1.3 [0.5, 2.2]	3	5	1.0 [0.0, 2.1]	2.1 [0.3, 3.8]
Trainers	20	22	2.2 [1.2, 3.1]	3.3 [1.9, 4.6]	6	7	2.0 [0.4, 3.6]	2.9 [0.8, 5.0]
Not classified	103	78	11.1 [9.1, 13.2]	11.6 [9.2, 14.0]	38	32	12.7 [8.9, 16.4]	13.2 [8.9, 17.4]

3.5 Discussion

This is the first study to report longitudinal medical attention incidence rates in professional ballet. Differences in medical attention incidence rates were observed across company rank, with First Soloists and Principals demonstrating an almost two-fold greater incidence rate compared with Apprentices. The time-loss injury incidence rate observed in this study is in line with published literature,[4,46,84–86] however, the severity of time-loss injuries was greater, with 35% of injuries resulting in more than 28 days of modified dance activity.[4,85] Consistent with previous research in professional ballet, most time-loss injuries were classified as overuse.[4,46,84] The most common mechanism of time-loss injury was jumping and landing activities, however, a similar number of injuries did not have a clear mechanism of injury.

3.5.1 Incidence Rate

No studies in professional ballet have previously reported medical attention injury incidence rates, however, the values observed in the present study are similar to those seen in professional contemporary dance.[198] The incidence rate of time-loss injuries in this study falls within ranges that are reported in professional ballet,[4,46,84,86] is comparable to cricket[43] and contemporary dance,[198] greater than that of modern dance,[199,200] but lower than rugby union or ice hockey.[41,55] In the absence of a direct comparison of activity profiles across dance genres, it is speculative to discuss differences in incidence rates between them. While time-motion analysis has revealed reduced activity demands in contemporary dance compared to ballet,[10] no such comparisons have been made between modern dance and ballet. Compared with invasion sports, however, the lower incidence rates observed in the present study may be due to fewer traumatic contact events during dance performance versus match play; incidence rates during rugby training, for example, are similar to those observed in the present study.[50]

First Soloists and Principals sustained between 2.0–2.2 additional medical attention injuries per 1000 hours and 0.9–1.1 additional time-loss injuries per 1000 hours compared with Apprentices. The transition period from pre-professional training into a professional ballet company has been previously identified as a potential risk factor for injury.[201] Our findings, however, demonstrate that Apprentices are at the lowest risk of injury compared with other company members. It is plausible that Apprentices may avoid disclosing injuries when trying to establish themselves within a new company. However, injury incidence rates are likely higher in senior ranking dancers due to the casting of more technically and physically demanding roles within these ranks compared with junior dancers.[189,202] The casting of roles and distribution of workload across company ranks is, however, at the discretion of the Artistic Director, and the utilisation of junior dancers may differ across ballet companies.

Between 2.0–2.8 additional medical attention injuries per 1000 hours were observed at the start (August and September) and end (June) of the season compared with mid-season. Higher medical attention injury incidence rates at the start of a season may suggest strategies are warranted for returning dancers, such as pre-season training or a more gradual reintroduction to ballet. The higher incidence rates observed at the end of the season may be influenced by dancers who have been managing medical issues during the season.[190] However, it should be noted that mixed bill productions, which demonstrate an additional 2.3 medical attention injuries and 0.8 and time-loss injuries per 1000 hours compared with full-length stand-alone productions, are more common later in the season. While inter-season differences in medical attention injury incidence rates were seen, no clear pattern was observed across the five seasons, potentially due to inter-season variation in repertoire. Understanding the incidence rates associated with production types may be beneficial to Artistic Directors and medical staff when planning and periodising a season.

3.5.2 Severity

The severity of time-loss injuries within the present study is almost two-fold greater than the severity previously published in professional ballet,[4] similar to football,[203] and lower than rugby union,[41,50] and volleyball.[51] Professional ballet has previously been described as a culture that normalises pain,[190,204,205] which may result in dancers not reporting medical issues and dancing through discomfort. We observed that 56% of all days lost to time-loss injury were classified as ‘restricted’ as opposed to ‘off’, suggesting that dancers may still have been participating in some form of dance activity while injured.

3.5.3 Injury Aetiology

Between 65–69% of medical attention and 50–51% of time-loss injuries were insidious and a consequence of overuse. The greater proportion of overuse injuries observed under the medical attention definition suggests that overuse injuries may be underestimated using a time-loss injury definition alone.[206] Previous studies in professional ballet have reported that a high proportion of time-loss injuries were overuse;[4,84] our results align with this, although it should be noted that inter-season variation was observed. The high frequency of overuse injuries observed may also be associated with the large exposure times; the scheduled exposure hours in professional dance is greater than that reported in sport.[51,189,199] The primary mechanism of time-loss injury was jumping and landing, in line with previous research.[4] We also observed a greater percentage of time-loss injuries associated with jumping and landing in men compared with women, however, the absolute number of injuries attributed to this mechanism was similar across sexes. In contrast to sport, where injuries principally occur in competition,[41,55,203] more than two-thirds of all time-loss injuries observed in the present study were attributed to training as opposed to performance. The higher proportion of training-related injuries is likely due to the 3.5-fold greater exposure hours observed during class and rehearsal compared with performance. Most injuries were classified as first episodes rather than recurrences, suggesting that time-loss injury rehabilitation is largely successful. The majority of injuries were classified as intrinsic, and may therefore provide an opportunity for training interventions or appropriate load management.[59,207–209]

3.5.4 Anatomical Region and Tissue Type

Previous research in professional ballet has reported injury region and tissue type inconsistently, making comparison with these studies challenging.[4,84–86] Generally, injuries to the distal lower extremity and joint/ligament tissue types demonstrated the greatest burden across all dancers. Ankle injuries pertaining to synovitis, impingement, and bursitis exhibited the greatest burden in female dancers, however, tendon and joint pathologies of the ankle were similar. *Pointe* positions, typically adopted by female dancers, require extreme range of motion of the ankle and may have negative consequences for musculoskeletal joint health. In male dancers, stress fractures to the foot and lower leg demonstrated the greatest burden. Nineteen of the twenty-one stress fractures recorded in men were attributed to jumping and landing activities and eighteen were non-traumatic. Medical management strategies addressing the joint and ligament injuries to the ankle in women and stress fractures to the foot and lower leg in men are warranted in this population.[210]

3.5.5 Strengths and Limitations

The strengths of this study include the prospective data entry from Chartered Physiotherapists, use of individualised prospectively entered dance exposure data, reporting of data through standardised entry forms, duration of data collection, consistency of the observed cohort, and the elite performance standard of the observed cohort.

Several limitations should be noted. Performance exposure was potentially inflated where individuals were allotted the total duration of a performance rather than on-stage time. Further, no register of attendance was taken for class or rehearsal, with attendance assumed but not verified. The authors, however, believe that it would be unusual for dancers to not attend scheduled dance events.

Multiple Chartered Physiotherapists were employed over the study period which may affect the uniformity of how injury data were gathered. It should be emphasised, however, that all physiotherapists used the same standardised entry forms and classification tools. The high frequency of overuse injuries may result in the misclassification of injury mechanism due to no traumatic inciting event.[8] Data describing injury region and tissue type were only presented for time-loss injuries, which may not represent all medical attention injuries. Four injuries were rehabilitating at the point of analysis and were subsequently removed from severity calculations. Finally, one ballet company was investigated and, thus, caution should be taken when generalising findings to other companies based on the season structure, hierarchy of company ranks, and casting of featured roles across company ranks.

3.6 Conclusion

This is the first prospective cohort study to investigate the longitudinal medical attention and time-loss injury incidence rates in a professional ballet company. First Soloists and Principals experienced medical attention and time-loss injury incidence rates roughly two-fold that of Apprentices. Although no differences in intra-season time-loss injury incidence rates were observed, 2.0–2.8 additional medical attentional injuries per 1000 hours were recorded at the beginning and end of the season compared with mid-season. The majority of injuries were overuse in nature and ~60% of all injuries occurred during training (rehearsal and class) compared with performance. The most common mechanism of time-loss injury was jumping and landing actions, however, many injuries were unclassified. Lower extremity injuries and injuries pertaining to joint and ligament tissue types caused the greatest burden. The results of this study may inform the design of targeted injury prevention interventions focusing on senior company ranks, intra-season variation, and jumping and landing activities in professional ballet dancers.

CHAPTER 4

Jumping in Ballet: A Systematic Review of Kinetics and Kinematics

4.1 Abstract

Objective To summarize research investigating kinetics and kinematics of jumping in ballet dancers.

Methods 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.

Results 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.

Conclusion The findings of this review can be used by dance science and medicine practitioners to improve their understanding of jumping in ballet dancers.

4.2 Introduction

Ballet dancers complete a high rate of jumping actions, exceeding that observed in contemporary dance[10] and comparable to that observed in volleyball.[211] Consistent with research in sport,[212] 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.[83] 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.[213,214] 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.[215,216] 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.[217–219] 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.[116,117,123,124] Dance research, however, has also investigated the influence of various internal (e.g., maturation,[220] sex,[71,221] and performance level[222]) and external (e.g., floor surface properties,[223,224] footwear,[225] and stage incline[226–228]) 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.

4.3 Methods

4.3.1 Search Strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis was used as a framework for this systematic review.[229] 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.

4.3.2 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.

4.3.3 Methodological Quality

The AXIS tool was used by the lead reviewer (AM) to critically appraise study design, reporting quality, and risk of bias.[230] 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.[231] 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.

4.3.4 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.[232] 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).[233] 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.

4.3.5 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.

4.4 Results

4.4.1 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 (Figure 4.1).[80,105,109,160,234–258]

4.4.2 Study Characteristics

A detailed overview of the results of the included studies is presented in Table 4.1. Twenty-one studies investigated ballet-specific jumps,[234,236–240,242–253,255,257,258] six investigated non-specific jumps,[105,160,235,241,254,256] and two investigated both ballet-specific and non-specific jumps.[80,109] Appendix A provides a glossary of included ballet-specific jumps. Nineteen studies exclusively investigated female ballet dancers,[80,160,234,236–238,241–243,245–252,254,256] two investigated males,[235,239] two investigated males and females,[240,258] and six did not specify the sex of participants.[105,109,243,253,255,257] Fourteen studies investigated adults,[80,105,109,234–238,240,242,243,247,249,251] ten investigated adolescents,[160,241,246,248,250,252,254,256–258] one investigated a mix of adults and adolescents,[253] and three did not specify the age of participants.[239,244,255] Nine studies investigated professional ballet dancers,[80,109,160,235,237,239,241,243,244] eighteen investigated non-professionals,[105,234,236,238,242,245,247–258] and two investigated a mix of professionals and non-professionals.[240,246] 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 4.2). 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 4.3).

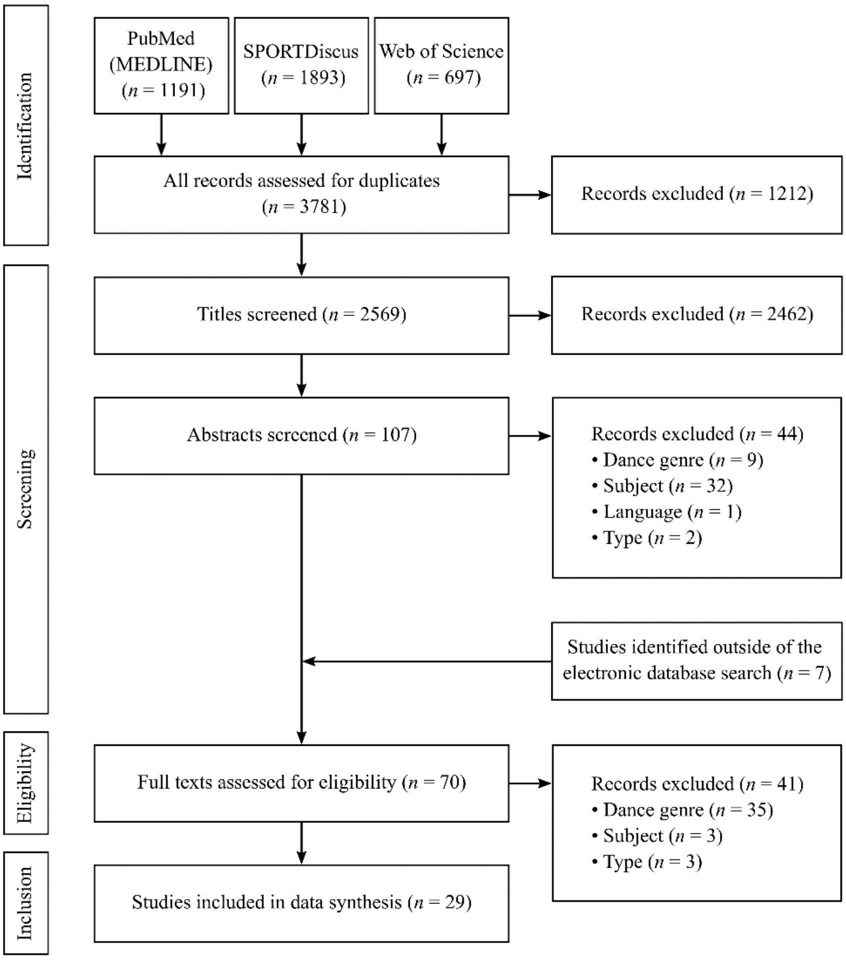


Figure 4.1 Flow diagram depicting the study search and selection process. Dance genre: studies excluded on the basis that participants were not primarily ballet dancers; Subject: studies excluded on the basis that kinetics or kinematics during take-off or landing phases of a jump were not assessed; Language: 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).

4.4.3 Critical Appraisal

The mean ± standard deviation (SD) critical appraisal score across included studies was 10.7 ± 3.7 out of 16 (Table 4.4). 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).

4.4.4 Kinetic Parameters

Six articles investigated kinetics during take-off and 19 articles investigated kinetics during landing (Table 4.2). Theoretical peak take-off power (~23–24 $W \cdot kg^{-1}$) and force (~22–24 $N \cdot kg^{-1}$) during a countermovement jump[160,241] and mean power during a Bosco repeated jump test (18 W·kg-1)[235] were reported in professional ballet dancers. Perry et al.[242] 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 >0.80). 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.[80,109]

Eleven articles reported peak landing vGRF, two of which provided absolute vGRF.[252,255] Six articles investigated ballet-specific jumps reporting relative peak landing vGRF values between 1.4–9.6 times body weight (BW),[243–245,248,250,258] 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.[105,246,256] An additional two articles investigated vGRF but did not report any data.[239,254] Five articles reported loading rate with values ranging between 9.5–222.7 $BW \cdot s^{-1}$ during a variety of ballet-specific landings;[240,243,244,248,250] however, two studies used sample sizes of 1[243] and 2[244] participants. Two articles investigated lower extremity joint stiffness during ballet-specific jumps, reporting the greatest values at the ankle[248] and knee.[238] Three articles investigated total stiffness of the lower extremity; two of which used a single dataset.[234,236]

Table 4.1 Jump kinetics and kinematics

Study	**Subject Characteristics (mean ± SD)**	**Jump Type**	**Equipment**	**Kinetics**		**Kinematics**	
				Measures	**Results**	**Measures**	**Results**
Mertz & Docherty[258]	*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.[109]	*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·kg^{-1}), knee (5.6 ± 1.1 Nm·kg^{-1}), hip (-3.1 ± 0.4 Nm·kg^{-1}) moment; average ankle (1.8 ± 0.3 Nm·kg^{-1}), knee (3.1 ± 0.2 Nm·kg^{-1}), and hip (-2.2 ± 0.3 Nm·kg^{-1}) moment; peak ankle (17.6 ± 3.7 W·kg^{-1}), knee (20.8 ± 9.5 W·kg^{-1}), and hip (-4.5 ± 1.2 W·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[245]	*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.	-	-

Table 4.1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	**Results**	**Measures**	**Results**
Imura & Iino[80]	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.

Table 4.1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	**Results**	**Measures**	**Results**
Hendry et al.[256]	*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[255]	*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.[239]	*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.	-	-

Table 4.1 Continued

Study	**Subject Characteristics (mean ± SD)**	**Jump Type**	**Equipment**	**Kinetics**		**Kinematics**	
				Measures	**Results**	**Measures**	**Results**
Picon et al.[253]	*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[235]	*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.[259] (81)	Jump mat	Mean power	Professional ballet dancers (18.1 ± 2.2 $W \cdot kg^{-1}$) demonstrated ↓ power compared to professional indoor soccer athletes (21.5 ± 4.2 $W \cdot kg^{-1}$), amateur bobsled athletes (21.9 ± 7.5 $W \cdot kg^{-1}$), and college basketball athletes (22.2 ± 5.8 $W \cdot kg^{-1}$).	-	-

Table 4.1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	**Results**	**Measures**	**Results**
Harwood et al.[254]	*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 hop in dancers compared to ND (13.4 ± 3.4° vs. 9.0 ± 4.1°, respectively). ↑ sagittal hip excursions in dancers compared to ND during the stop jump (13.4 ± 4.1° vs. 9.7 ± 3.3°, respectively). ↑ ankle PF (dancers hop: 33.4 ± 9.0°; ND hop: 17.3 ± 8.5°; dancers stop jump: 31.9 ± 7.3°; ND stop jump: 22.3 ± 9.7°), sagittal ankle excursions (dancers hop: 58.6 ± 6.8°; ND hop: 36.6 ± 9.5°; dancers stop jump: 45.5 ± 2.0°; ND stop jump: 30.7 ± 10.8°), knee EXT prior to landing (dancers hop: 2.1 ± 4.5°; ND hop: 13.8 ± 7.4°; dancers stop jump: 2.9 ± 5.1°; ND stop jump: 8.1 ± 5.2°), sagittal knee excursions (dancers hop: 51.8 ± 12.0°; ND hop: 33.7 ± 13.6°; dancers stop jump: 48.3 ± 9.4°; ND stop jump: 38.5 ± 6.6°), hip EXT prior to landing (dancers hop: 12.0 ± 5.9°; ND stop jump: 20.0 ± 9.4°; dancers stop jump: 20.6 ± 7.2°; ND stop jump: 34.7 ± 8.7°), and ↓ hip FLEX angles (dancers: 34.1 ± 5.8°; ND: 44.4 ± 8.6°) in dancers compared to ND. ↔ in horizontal approach velocity during the stop jump.
Hackney et al.[234]	*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.	-	-

Table 4.1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	Results	Measures	Results
Fong Yan et al.[249]	*n* = 16 F uninjured NP ballet dancers (Age = 25.0 ± 5.9 y; Mass = 55.9 ± 7.4 kg)	*Sauté* in 2nd 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°), and transverse midfoot (chorus: 5.0 ± 2.1; barefoot: 13.3 ± 5.0°) ROM observed in chorus 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.[238]	*n* = 16 F uninjured NP ballet dancers (Age = 25.0 ± 5.9 y; Mass = 56.0 ± 7.4 kg)	*Sauté* in 2nd 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.	-	-

Table 4.1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	**Results**	**Measures**	**Results**
Hackney et al.[236,251]	*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.[247]	*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$^{\circ}\cdot s^{-1}$; stiff: 513 ± 47$^{\circ}\cdot s^{-1}$). ↔ in ankle and hip peak angles or velocities was observed across floor conditions.
Volkerding & Ketcham[105]	*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 4.1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	**Results**	**Measures**	**Results**
Almonroeder et al.[246]	*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), 50% (4.7 ± 0.5 g), 75% (4.7 ± 0.4 g), and 100% (4.7 ± 0.4 g) of test compared to baseline (4.2 ± 0.9 g). +ve relationships were observed between peak impact acc and peak vGRF (range: r = 0.95 to 0.98) and LR (range: r = 0.80 to 0.88) across all time points.
Peng et al.[248]	*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 ± 19.7°) angle under fatigue compared to no fatigue. ↓ Ankle DF (no fatigue: 60.1 ± 9.6°; fatigue: 54.8 ± 14.2°) excursion during landing under fatigue compared to no-fatigue. ↔ in any other excursion or joint angle at initial contact or the position of lowest COM across all joints, injury, and fatigue conditions.

Table 4.1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	**Results**	**Measures**	**Results**
Arnwine & Powell[240]	*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·kg·s^{-1}, respectively) but not *Sauté* (0.29 ± 0.03 vs. 0.29 ± 0.06 N·kg·s^{-1}, respectively). ↑ loading rate in females compared to males during *Grand Jeté* (78.2 ± 9.3 vs. 49.9 ± 15.6 BW·s^{-1}, respectively) but not *Sauté* (16.1 ± 4.7 vs. 18.5 ± 9.0 BW·s^{-1}, respectively).	-	-
Escobar Álvarez et al.[241]	*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-V$_{IMB}$	Peak Fz was 25.2 ± 2.0 N·kg^{-1}, peak power was 23.0 ± 4.1 W·kg^{-1}, and F-V$_{IMB}$ was 45.6 ± 13.5%. Soloists (27.3 ± 4.6 W·kg^{-1}) demonstrated ↑ peak power compared to Second Soloists (23.5 ± 3.0 W·kg^{-1}). Soloists and Second Soloists demonstrated ↑ peak power compared to the *Corps de Ballet* (20.9 ± 3.2 W·kg^{-1}).	Peak velocity	Peak velocity was 3.7 ± 0.8 m·s^{-1}. Soloists (4.2 ± 0.8 m·s^{-1}) and Second Soloists (3.8 ± 0.7 m·s^{-1}) demonstrated ↑ peak velocity compared to the *Corps de Ballet* (3.4 ± 0.7 m·s^{-1}).
Perry et al.[242]	*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·kg^{-1}, respectively), peak ankle joint moment (3.03 ± 0.40 vs. 2.61 ± 0.38 Nm·kg^{-1}, respectively), mean RFD (103.3 ± 35.6 vs. 74.4 ± 17.8 N·s·kg^{-1}, respectively), and peak ankle power (20.7 ± 4.7 vs. 15.6 ± 3.5 W·kg^{-1}) was observed during the *Saut de Chat* compared to the *Temp Levé*.	-	-

Table 4.1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	**Results**	**Measures**	**Results**
Lee et al.[250]	*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-tibia eversion (injured: 0.6 ± 17.1°; uninjured: 10.4 ± 13.7°) in previously injured dancers compared to uninjured dancers. ↔ across all other joint angles.
Escobar Álvarez et al.[160]	*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; $F\text{-}V_{IMB}$	↑ 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}). ↓ $F\text{-}V_{IMB}$ 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: 4.2 ± 0.7; EG: 3.2 ± 0.5 m·s^{-1}).
Hendry et al.[257]	*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 1st and 2nd 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 1st. ↔ in knee and hip Fz when jumping in 2nd. ↓ 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 1st (knee FLEX range: 56.6 ± 18.2° to 58.0 ± 18.8°; hip FLEX range: 39.7 ± 12.4° to 40.9 ± 12.4°), 2nd (knee FLEX range: 61.1 ± 19.2° to 61.5 ± 18.2°; hip FLEX range: 41.6 ± 12.5° to 42.3 ± 14.2°), or temp leve (knee FLEX range: 56.6 ± 18.2° to 58.0 ± 18.8°; hip FLEX range: 39.0 ± 11.5° to 41.9 ± 12.3°).

Table 4.1 Continued

Study	**Subject Characteristics (mean ± SD)**	**Jump Type**	**Equipment**	**Kinetics**		**Kinematics**	
				Measures	**Results**	**Measures**	**Results**
Walter, Docherty, & Schrader[252]	*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[237]	*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 1st 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 time to peak acc.

Table 4.1 Continued

Study	Subject Characteristics (mean ± SD)	Jump Type	Equipment	Kinetics		Kinematics	
				Measures	**Results**	**Measures**	**Results**
Gorwa et al.[243]	*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.[244]	*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 4.2 Jump phases

Study	**Take-Off**		**Landing**	
	Kinetics	**Kinematics**	**Kinetics**	**Kinematics**
Ravn et al.[109]	*			
Perry et al.[242]	*			
Kirkendall & Street[235]	*			
Escobar Álvarez et al.[241]	*	*		
Escobar Álvarez et al.[160]	*	*		
Imura & Iino[80]	*	*		
Harwood et al.[254]		*	*	*
Arnwine & Powell[240]			*	
Dworak et al.[244]			*	
Chockley[255]			*	
Miller et al.[239]			*	
Hackney et al.[251]			*	
Hackney et al.[234]			*	
Hackney et al.[236]			*	
Walter, Docherty, & Schrader[252]			*	
Fong Yan et al.[238]			*	
Mertz & Docherty[258]			*	
McPherson, Schrader, & Docherty[245]			*	
Volkerding & Ketcham[105]			*	*
Hendry et al.[257]			*	*
Almonroeder et al.[246]			*	*
Peng et al.[248]			*	*
Lee et al.[250]			*	*
Hendry et al.[256]			*	*
Gorwa et al.[243]			*	*
Picon et al.[253]				*
Hackney et al.[247]				*
Couillandre, Lewton-Brain, and Portero[237]				*
Fong Yan et al.[249]				*

Table 4.3 Organizational themes

Study	**Environment & Equipment**	**Activity Type**	**Demographics**	**Physical Characteristics**	**Injury Status**	**Skill Acquisition & Motor Control**
Miller et al.[239]	*					
Hackney et al.[251]	*					
Hackney et al.[247]	*					
Hackney et al.[234]	*					
Hackney et al.[236]	*					
Walter, Docherty, & Schrader[252]	*					
Fong Yan et al.[249]	*					
Fong Yan et al.[238]	*					
Hendry et al.[257]	*					
McPherson, Schrader, & Docherty[245]	*	*				
Chockley[255]		*				
Perry et al.[242]		*				
Imura & Iino[80]		*				
Gorwa et al.[243]		*				
Dworak et al.[244]		*				
Mertz & Docherty[258]		*				
Ravn et al.[109]		*	*			
Volkerding & Ketcham[105]		*	*			
Arnwine & Powell[240]		*	*			
Picon et al.[253]			*			
Kirkendall & Street[235]			*			
Hendry et al.[256]			*			
Harwood et al.[254]			*			
Escobar Álvarez et al.[241]			*			
Escobar Álvarez et al.[160]				*		
Almonroeder et al.[246]				*		
Peng et al.[248]				*	*	
Lee et al.[250]					*	
Couillandre, Lewton-Brain, and Portero[237]						*

Table 4.4 Appraisal scores using the AXIS tool

Study	Intro.	Methods										Results					Discussion		Other		Total / 16
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Chockley[255]	0	0	0	0	0	1	-	0	0	0	0	0	-	-	-	0	0	0	0	1	2
Miller et al.[239]	1	1	0	0	0	1	-	0	0	0	0	0	-	-	-	0	0	0	0	0	3
Dworak et al.[244]	1	0	0	0	0	1	-	0	1	0	0	0	-	-	-	0	0	0	1	1	5
Couillandre, Lewton-Brain, and Portero[237]	0	0	0	1	0	1	-	0	0	1	0	0	-	-	-	1	0	1	0	1	6
Hackney et al.[251]	1	1	1	0	0	1	-	1	0	0	0	0	-	-	-	1	0	0	0	1	7
Gorwa et al.[243]	1	1	0	1	0	1	-	1	0	0	0	1	-	-	-	1	0	0	1	0	8
Mertz & Docherty[258]	0	0	0	0	1	1	-	0	0	1	0	1	-	-	-	1	1	1	0	1	8
Hackney et al.[247]	1	1	0	0	1	1	-	1	0	0	1	0	-	-	-	0	0	1	0	1	8
Hackney et al.[234]	1	1	0	0	1	1	-	1	0	0	1	0	-	-	-	1	0	1	0	1	9
Hackney et al.[236]	1	1	0	1	0	1	-	1	0	0	1	1	-	-	-	1	1	0	0	0	9
Ravn et al.[109]	1	1	0	0	1	1	-	1	1	1	0	1	-	-	-	1	1	0	0	0	10
Walter, Docherty, & Schrader[252]	1	1	0	1	1	1	-	1	1	1	0	0	-	-	-	1	0	0	0	1	10
Picon et al.[253]	1	1	1	0	1	1	-	1	1	1	0	0	-	-	-	0	0	1	0	1	10
Arnwine & Powell[240]	1	1	0	1	1	1	-	1	1	0	0	1	-	-	-	1	0	1	0	1	11
Kirkendall & Street[235]	1	1	0	0	1	1	-	1	1	1	1	1	-	-	-	1	1	0	0	0	11
Fong Yan et al.[249]	1	1	0	0	1	1	-	1	1	1	1	1	-	-	-	0	0	1	0	1	11
Fong Yan et al.[238]	1	1	0	1	1	1	-	0	0	1	0	1	-	-	-	1	1	1	0	1	11
McPherson, Schrader, & Docherty[245]	1	1	0	1	1	1	-	1	0	1	0	1	-	-	-	1	1	1	0	1	12
Volkerding & Ketcham[105]	1	1	0	0	1	1	-	1	1	1	1	1	-	-	-	1	1	1	0	1	13
Hendry et al.[257]	1	1	0	0	1	1	-	1	1	1	1	1	-	-	-	1	1	1	0	1	13
Lee et al.[250]	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	0	1	14
Escobar Álvarez et al.[241]	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	0	1	14
Escobar Álvarez et al.[160]	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	0	1	14
Hendry et al.[256]	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	0	1	14
Perry et al.[242]	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	1	1	15
Peng et al.[248]	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	1	1	15
Imura & Iino[80]	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	1	1	15
Almonroeder et al.[246]	1	1	0	1	1	1	-	1	1	1	1	1	-	-	-	1	1	1	1	1	15
Harwood et al.[254]	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 ± 3.7

Intro. Introduction

4.4.5 Kinematic Parameters

Four articles investigated kinematics during take-off and 12 articles investigated kinematics during landing (Table 4.2). 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.[80] Theoretical take-off velocity was reported as 3.7–4.2 $m \cdot s^{-1}$ during CMJs in two articles.[160,241] 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.[237,243,247–250,257] 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.[105,254,256] 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.[254,256] Hackney et al.[247] reported slightly higher peak joint velocities at the ankle compared to the knee upon landing from an échappé sauté (512.6 ± 47.3 vs. $343.7 \pm 86.1 ^\circ \cdot s^{-1}$, respectively). Two articles investigated impact acceleration upon landing from ballet-specific jumps,[237,246] one of which illustrated positive relationships between impact acceleration and peak landing vGRF.[80]

4.4.6 Activity Type

Ten studies investigated the influence of different jumping and landing activities on the kinetics and kinematics of ballet dancers (Table 4.3). Reduced knee moments were observed during the take-off of a ballet jump when compared to a CMJ in two studies.[80,109] Although not significant, greater ankle moments, power, and work were observed during CMJs compared to ballet jumps in both articles.[80,109] Imura and Iino[80] 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.[242]

McPherson, Schrader, and Docherty[245] 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,[240] 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.[255] Gorwa et al.[243] 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.[243] 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.[244] reported 8 different ballet jumps demonstrating vGRF between 5.3–9.4 BW and loading rates between 26.2–128.5 $\mathrm{BW \cdot s^{-1}}$, 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 4.4).

4.4.7 Demographics

Six studies investigated kinetic and kinematic differences across demographics during take-off and landing in ballet dancers (Table 4.3). 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.[160] 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.[235] 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.[109] Critical appraisal scores ranged from 10-16 (Table 4.4).

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.[254,256] 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.[105] Harwood et al.[254] 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.[240]

4.4.8 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 4.3), two of which reported the same data.[236,251] When ballet flats and barefoot conditions have been investigated, no differences in peak landing vGRF were reported,[239,245] whereas landing in *pointe* shoes has demonstrated smaller peak landing vGRF compared to ballet flats (1743 ± 253 vs. 1613 ± 262 N).[252] 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 $\text{Nmm}\cdot\text{deg}^{-1}$) compared to barefoot.[238,249] 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.[234,236,251] Hackney et al.[247] observed reduced knee angles (55.2 ± 11.5° vs. 57.8 ± 9.6°) and ankle velocities ($492 \pm 50°\cdot\text{s}^{-1}$ vs. $513 \pm 47°\cdot\text{s}^{-1}$) 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.[257] In two studies, no statistical tests were conducted.[239,255] Critical appraisal scores ranged from 3–13 (Table 4.4).

4.4.9 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 4.3). Individualized training programs, based on force-velocity profiling, improve force-velocity imbalances in professional ballet dancers, primarily through increased force production during take-off.[160] Almonroeder et al.[246] reported increased peak landing vGRF, loading rate, and acceleration across the duration of a dance-specific fatiguing protocol. Conversely, Peng et al.[248] 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.[248] Critical appraisal scores ranged from 14–15 (Table 4.4).

4.4.10 Skill Acquisition and Motor Control

No differences were observed in kinematic variables following a mental imagery intervention in adult female professional ballet dancers.[237] The critical appraisal score was 6/16 (Table 4.4).

4.4.11 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 4.3). Lee et al.[250] 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 $BW \cdot s^{-1}$) and greater ankle eversion (11.9 ± 7.6 vs. 8.1 ± 2.9°) in previously injured dancers. Peng et al.[248] 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[250] and 15[248] out of 16 (Table 4.4).

4.5 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 $BW \cdot s^{-1}$), however, large ranges were observed, potentially due to small sample sizes and different technical demands across jumps.[240,243,244,248,250] 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.[80,109] 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.[254,256] 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.

4.5.1 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.[80,109] Greater lower extremity external rotation and smaller hip and trunk flexion were observed by Imua and Iino,[80] 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.[260,261] Although no differences in hip extensor torque were observed in professional ballet dancers between a CMJ in parallel and turnout,[80] smaller hip moments, power, and work have been observed in professional dancers when compared to professional volleyball athletes.[109] 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.[245] investigated unilateral and bilateral ballet jumps, observing greater peak landing vGRF during a *grand jeté* compared to an *assemblé*. Arnwine and

Powell[240] reported similar data, supporting the findings of greater landing vGRFs in unilateral landings. Conversely, Pappas et al.[262] 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,[243,244] 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 4.4) making the interpretation challenging. Perry et al.,[242] 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[255] 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.[186,263]

4.5.2 Demographics

No sex differences in the rate of jumping during a performance[10] 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.[254,256] Greater lower extremity extension upon landing has been previously cited as an injury risk factor, due to increased lower extremity stiffness,[264] however, greater extension prior to landing has been associated with both stiff and compliant landings.[81,264] 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.[254,256] 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.[71] Knee valgus patterns were present in adolescent female ballet dancers, but not non-dancers in two studies,[254,256] and one study identified greater vGRF in female ballet dancers when compared to their male counterparts.[240] 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,[265] as well as improved ability to maintain external rotation during take-off and landing when compared to adolescent and adult ballet dancers.[253] It is plausible that early specialization in one dance genre, such as ballet, may lead to reduced athletic development in place of technical advancement.[266]

No differences in relative peak landing vGRF have been observed between adult or adolescent ballet dancers and non-dancers during various landing tasks.[105,254,256] The lack of significant differences across adolescent ballet dancers and non-dancers may be attributed to relatively similar training backgrounds.[267] It is only when ballet dancers engage in pre-professional or professional training that rehearsal volume significantly increases;[4,268] 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.[117]

4.5.3 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.[252] No differences in landing vGRF were observed between ballet flats and barefoot.[239,245] Footwear has shown no effect on peak landing vGRF in athletes, except in the instance of unanticipated landings.[269–272] 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.[273] When landing in character shoes, increased knee excursions and reduced knee stiffness is observed compared to barefoot.[238,249] In athletic populations, increasing heel heights have been shown to reduce vGRF and increase the speed of lower extremity muscle activation.[274,275] 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.[276] 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.[234,236,247,251] 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.[224] 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.[224] postulated that traditional hard flooring requires greater neuromuscular control which may be associated with injury in dancers.

4.5.4 Physical Characteristics

Increasingly, ballet dancers engage in supplementary training to improve physical characteristics such as muscular strength and fatigue resistance to facilitate their preparation.[277] Individualized training programs improve force-velocity imbalances in professional ballet dancers, primarily through increased force production during take-off.[160] 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.[10,124] Inconsistent findings are reported in peak landing vGRF responses to a fatigue protocol in ballet dancers.[246,248] 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.[248] Jayalath et al.[278] 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.

4.5.5 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.[237] 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.[102,279] 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.

4.5.6 Injury Status

Current and previous lower extremity injury results in altered landing biomechanics when compared to uninjured ballet dancers,[248,250] 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.[279,280] Comprehensive return-to-play criteria exist within sport, facilitating a graded rehabilitation, and should serve as a framework when developing return-to-dance pathways.[281] Consideration of jumping within return-to-dance pathways is especially important in ballet due to the frequency and intensity of such actions during performance.[10]

4.5.7 Limitations

One limitation of the present review is that the participant's 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.

4.5.8 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 4.1). 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 4.2). Future research may wish to utilize previously reported methods to investigate jump phases more comprehensively in ballet dancers.

4.6 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.

SECTION 2: GENERAL METHODS

CHAPTER 5

Reliability, Variability, and Minimal Detectable Change of Bilateral and Unilateral Lower Extremity Isometric Force Tests

5.1 Abstract

Objective To investigate the within- and between-session reliability, variability, and minimal detectable change (MDC) of vGRF during bilateral and unilateral lower extremity maximal isometric force tests.

Methods Eighteen participants (men: n = 9, age: 27.9 ± 6.3 y, height: 1.82 ± 0.06 m, mass: 82.4 ± 10.4 kg, strength training experience: 10.4 ± 7.7 y; women: n = 9, age: 29.3 ± 8.6 y, height: 1.68 ± 0.01 m, mass: 58.0 ± 5.8 kg, strength training experience: 5.5 ± 3.6 y) attended two data collection sessions separated by 48 h. The absolute, net, and relative vGRF were calculated across bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions.

Results All measures of vGRF demonstrated excellent reliability and low variability within (intraclass correlation coefficients (ICC): 0.92–0.99; coefficient of variation (CV): 2.9–6.5%) and between sessions (ICC: 0.95–1.00; CV: 2.0–6.0%), across all positions. The MDC ranged between 135–276 N (5.1–14.5%), with the seated plantarflexion positions demonstrating the highest values as a percentage of the group mean (13.3–14.5%).

Conclusion Maximal isometric force testing during bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions provide reliable measures of vGRF in men and women.

5.2 Introduction

Maximal isometric force testing is a common method used to measure lower extremity strength. Research investigating the reliability of maximal isometric force tests has largely been conducted on the isometric mid-thigh pull using a force platform and general isometric rig.[182] The isometric squat and seated and standing ankle plantarflexion have been reported in the literature, however, these investigations have used highly specialized equipment such as hack squat machines ,[282,283] wall-mounted force platforms,[284] or bespoke seated force transducers.[285] Specialized equipment for these tests may offer limited utility in applied environments due to cost and space restrictions. Conversely, the ability to test across various positions using a force platform and general isometric rig offers science and medicine practitioners a practical approach to isometric force testing.

Whilst bilateral variations of maximal isometric force tests have been the most common positions investigated when establishing the reliability of lower extremity strength characteristics,[182] there is increasing interest in unilateral variations.[286–288] Unilateral variations of maximal isometric force tests offer insights into the strength characteristics of the limb and inter-limb asymmetries thereof.[286] Inter-limb asymmetries are particularly valuable when developing criteria-led return-to-sport protocols following unilateral injury,[289] or when directing the emphasis of training in non-injured individuals.[287] A combination of bilateral and unilateral strength characteristics and asymmetries can also be used to inform programming decisions relating to exercise selection.[290,291] Limited research, however, has investigated the effect of both bilateral and unilateral stance on the reliability of strength characteristics during various isometric force tests.[283]

The within-session reliability and variability of isometric force tests are well documented, with peak vGRF demonstrating the greatest ICC and smallest CV compared with other variables (e.g., rate of force development).[182] The between-session reliability and variability of peak vGRF during isometric force testing, however, are less well documented.[182] In addition to characterizing reliability, between-session ICCs can be used to calculate the MDC. The MDC has been used to establish thresholds for outcome variables, such as vGRF, enabling practitioners to differentiate signal from noise and identify a meaningful change [292]. No studies, however, have determined the MDC during the unilateral squat or bilateral or unilateral ankle plantarflexion variations of maximal isometric force tests.[182] Data pertaining to the reliability, variability, and MDC in these positions would provide a basis for applied practitioners to use such methods to monitor neuromuscular changes specific to these positions and muscle groups.

This study aimed to investigate the within- and between-session reliability, variability, and MDC of vGRF measures during maximal isometric force tests across bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions.

5.3 Methods

5.3.1 Study Design

A within-subject test-retest design was employed to investigate the reliability, variability, and MDC of vGRF during the isometric squat, standing plantarflexion, and seated plantarflexion tests. Two or more replicants were required to calculate ICCs ($\alpha = 0.05$, $\beta = 0.80$) based on a minimal acceptable reliability (ρ_0) of ≥ 0.7,[293] and expected reliability (ρ_1) of ≥ 0.9.[182] The expected reliability of ≥ 0.9 was based on previous research demonstrating excellent reliability for measures of vGRF.[182] *A priori* power analyses indicated that minimum samples of eighteen participants were required to calculate the ICC ($\alpha = 0.05$, $\beta = 0.80$), based on two trials recorded per participant,[294] a ρ_0 of ≥ 0.7,[294] and a ρ_1 of ≥ 0.9.[182] Internal training load was calculated for the 48 h preceding testing to account for differences in training load prior to testing sessions. Internal training load was calculated using the session rating of perceived exertion method for each participant, where rating of perceived exertion using the Borg CR-10 was multiplied by session duration in minutes.[295] The time of day was standardized for each participant to account for variations in circadian rhythm.[296]

5.3.2 Participants

Nineteen participants volunteered for this research, of which eight were professional ballet dancers (men: *n* = 4; women: *n* = 4) and eleven physically active men (*n* = 6) and women (*n* = 5). One participant withdrew following the first testing session resulting in eighteen participants (men: *n* = 9, age: 27.9 ± 6.3 y, height: 1.82 ± 0.06 m, mass: 82.4 ± 10.4 kg, strength training experience: 10.4 ± 7.7 y; women: *n* = 9, age: 29.3 ± 8.6 y, height: 1.68 ± 0.01 m, mass: 58.0 ± 5.8 kg, strength training experience: 5.5 ± 3.6 y). Participants were required to have not sustained an injury in the six weeks prior to data collection. Written informed consent was gained from all participants and ethical approval was provided by the local Ethics Committee in accordance with the Declaration of Helsinki (Appendix C).

5.3.3 Procedures

All participants attended two identical data collection sessions, separated by 48 h. The first session was used to establish within-session reliability and variability. The first and second sessions were used to establish between-session reliability, variability, and the MDC. During each session, participants performed three five-second maximal isometric contractions in the bilateral squat, unilateral squat, bilateral standing plantarflexion, unilateral standing plantarflexion, bilateral seated plantarflexion, and unilateral seated plantarflexion positions (Figure 5.1). All unilateral tests were completed on the right limb only to limit the number of maximal isometric contractions within the testing session. Each five-second maximal isometric contraction within a position was separated by a 20 s recovery period. A further two-minute recovery period was provided once three maximal isometric contractions were completed within a position. A standardized and progressive warm-up was completed prior to testing, including bodyweight exercises and submaximal isometric contractions across the testing positions. The vGRF data were collected using a force platform (MUSCLELAB, Ergotest Innovation AS, Stathelle, Norway) sampling at 1000 Hz. An isometric rig, with 2.5 cm adjustable vertical spacing, and a barbell (Sportesse, Somerset, United Kingdom) were used for all tests, with a 3.3 cm thick foam pad (Power Guidance, London, England) around the barbell for comfort. Bodyweight was calculated from a five-second static trial where participants were standing motionless on the force platform. Participants were required to wear their own shoes (and the same shoes) for all testing sessions. Participants were instructed to “push maximally into the barbell” before each trial. Each trial was initiated by the researcher instructing the participant to adopt the relevant position and then counting down “3, 2, 1, Push”. The force platform was zeroed prior to each set.

Figure 5.1 A) Bilateral squat B) Unilateral squat C) Bilateral standing plantarflexion D) Unilateral standing plantarflexion E) Bilateral seated plantarflexion F) Unilateral seated plantarflexion.

5.3.3.1 Isometric Squat

The barbell was placed in a high-bar back squat position on the upper trapezius. Using a goniometer, knee and hip angles were measured to 140°, where full knee and hip extension were considered 180°.[182] Knee angle was calculated by positioning the fulcrum of the goniometer over the lateral epicondyle of the femur, with the stabilization arm in line with the lateral malleolus and the movement arm in line with the greater trochanter. Hip angle was calculated by positioning the fulcrum of the goniometer over the greater trochanter with the stabilization arm in line with the femur and the movement arm in line with the glenohumeral joint. During bilateral tests, the feet were positioned at hip width. For unilateral tests, the contralateral limb was held in 90° of hip flexion to maintain a neutral hip position.

5.3.3.2 Isometric Standing Plantarflexion

The barbell was placed in a high-bar back squat position. Participants were instructed to adopt a “soft knee” position (170–180°) to avoid hyperextension. Participants were also instructed to adopt a “neutral” hip position (170–180°), measured by placing the fulcrum of the goniometer over the greater trochanter with the stabilization arm in line with the femur and the movement arm in line with the glenohumeral joint. The ankle was measured to 130° of plantarflexion. A plantarflexed position was selected over plantar grade or relative dorsiflexion to reduce the requirement of additional equipment (i.e., a heel raise block) and account for different heel drop heights across participant shoes. Ankle angle was calculated by positioning the fulcrum of the goniometer over the lateral malleolus with the stabilization arm in line with the head of the fibular and the movement arm in line with the first metatarsophalangeal joint. The ball of the foot was placed directly underneath the barbell. During bilateral tests, the feet were positioned at hip width. During unilateral tests, the contralateral limb position was the same as outlined in the squat protocol.

5.3.3.3 Isometric Seated Plantarflexion

The barbell was placed proximal to the patella on the quadriceps while participants were seated in 90° of knee and hip flexion. Knee and hip measurement techniques were consistent with those outlined in the squat and standing plantarflexion protocols. Ankle position was measured using the same methods outlined in the standing plantarflexion protocol. Participants were instructed to place their arms across their shoulders to avoid assistance from the upper limb. During bilateral tests, the feet were positioned at hip width. During unilateral tests, the contralateral limb was resting off the force platform to avoid assistance.

5.3.4 Statistical Analysis

Mean vGRF was extracted during static bodyweight trials and peak vGRF, hereon referred to as absolute vGRF, was extracted during maximal isometric trials directly from the force platform software. No filtering was applied to vGRF data. Body mass was calculated by dividing mean vGRF during the static bodyweight trial by the acceleration of gravity. Net and relative vGRF was calculated to account for the influence of body mass. Net vGRF was calculated by subtracting bodyweight from absolute vGRF. Relative vGRF was calculated by dividing the absolute vGRF by body mass. The mean ± standard deviation (SD) of the absolute, net, and relative vGRF was calculated from the three trials in each position.

The within-session reliability of absolute, net, and relative vGRF was established by calculating the ICCs, with 95% confidence intervals (CI), across the three trials in each position using the *irr* R package.[297] The between-session reliability of absolute, net, and relative vGRF (mean of the three trials) was established by calculating the ICCs, with 95% CI, across the two testing sessions in each position. Two-way mixed-effects models (type = agreement) were used to calculate ICCs for within- and between-session reliability.[293] The ICC was interpreted in line with Koo and Li (2016) where < 0.50 = Poor; 0.50–0.75 = Moderate; 0.75–0.90 = Good; > 0.90 = Excellent. The within- and between-session intra-subject variability of the absolute, net, and relative vGRF was established by computing the CV using the *EnvStats* R package.[298] Standard error of measurement (SEM) was calculated using the following equation:

$$SEM = SD_{baseline}\sqrt{1 - ICC_{between}}$$

Where $SD_{baseline}$ was considered the between-subject SD of the absolute, net, and relative vGRF during the first testing session, and $ICC_{between}$ was considered the between-session ICC.[299] The MDC was calculated using the following equation:

$$MDC = 1.96 \times \sqrt{2} \times SEM$$

Following checks for outliers, normality, and equal variance, a paired samples Wilcoxon signed-rank test was used to investigate differences in the mean internal training load between sessions using the *stats* R package.[300] All data processing and statistical analysis were conducted using R (version 4.0.3, R Foundation for Statistical Computing, Vienna, Austria).

Table 5.1 Within-session intraclass correlation coefficient and coefficient of variation

Position	***n***	**Absolute vGRF (N)**		**Net vGRF (N)**		**Relative vGRF (N·kg^{-1})**	
		ICC (95% CI)	**CV**	**ICC (95% CI)**	**CV**	**ICC (95% CI)**	**CV**
DL Squat	18	0.99 (0.98–1.00)	2.9	0.99 (0.97–1.00)	4.1	0.97 (0.94–0.99)	2.9
SL Squat	18	0.98 (0.96–0.99)	3.5	0.98 (0.95–0.99)	5.2	0.96 (0.92–0.98)	3.5
DL Standing PF	18	0.96 (0.91–0.98)	4.4	0.94 (0.88–0.98)	6.5	0.92 (0.84–0.97)	4.4
SL Standing PF	18	0.97 (0.94–0.99)	3.2	0.96 (0.91–0.98)	5.2	0.93 (0.86–0.97)	3.2
DL Seated PF	18	0.94 (0.88–0.98)	6.1	-	-	0.93 (0.85–0.97)	6.1
SL Seated PF	18	0.95 (0.89–0.98)	5.4	-	-	0.93 (0.85–0.97)	5.4

DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; ICC, Intraclass Correlation Coefficient; CV, Coefficient of Variation; vGRF, Vertical Ground Reaction Force; CI, Confidence Interval.

5.4 Results

Differences in internal training load in the 48 h prior to the first (mean ± SD: 825 ± 886, range: 0–2460 Arbitrary Units [AU]) and second (mean ± SD: 1253 ± 1135, range: 200–3705 AU) data collection sessions ($Z = -2.5$, $p = .014$) was observed. The within- and between-session ICC, CV, SEM, and MDC of the absolute, net, and relative vGRF are reported in Tables 5.1 and 5.2. Mean ± SD and 95% confidence intervals for the absolute, net, and relative vGRF can be found in Table 5.3. Box plots and individual test-retest absolute, net, and relative vGRF data are shown in Figure 5.2. Box plots and individual differences in absolute, net, and relative vGRF between the bilateral and unilateral variations of each testing position can be seen in Figure 5.3.

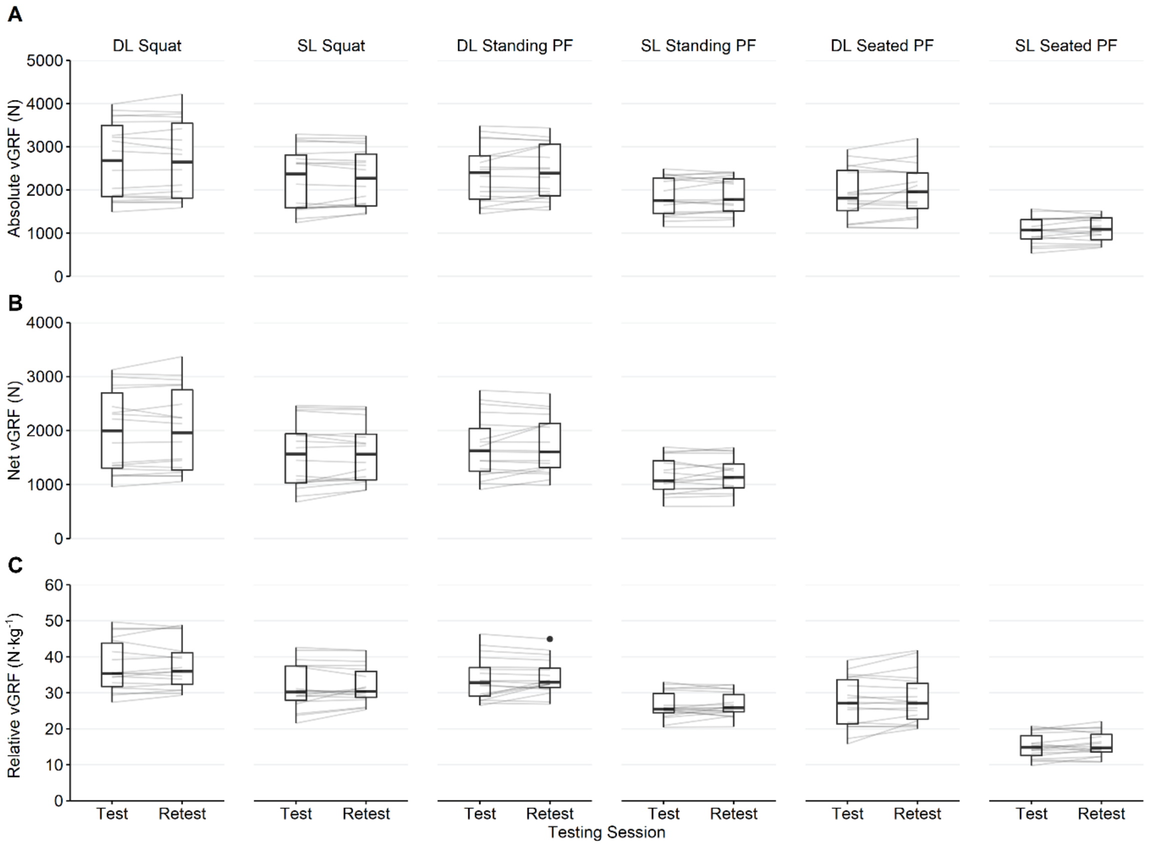


Figure 5.2 Box plots and individual test-retest absolute A), net B), and relative C) vertical ground reaction force data. DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; vGRF, Vertical Ground Reaction Force.

Table 5.2 Between-session intraclass correlation coefficient, coefficient of variation, standard error of measurement, and minimal detectable change

Position	***n***	**Absolute vGRF (N)**				**Net vGRF (N)**				**Relative vGRF (N·kg^{-1})**			
		ICC [95% CI]	**CV**	**SEM [95% CI]**	**MDC (%)**	**ICC [95% CI]**	**CV**	**SEM [95% CI]**	**MDC (%)**	**ICC [95% CI]**	**CV**	**SEM [95% CI]**	**MDC (%)**
DL Squat	18	1.00 [0.99, 1.00]	2.0	49 [0, 144]	135 (5.1)	1.00 [0.99, 1.00]	2.8	51 [0-150]	140 (7)	0.99 [0.97, 1.00]	2.4	0.8 [0.0-2.3]	2.2 (5.8)
SL Squat	18	0.99 [0.98, 1.00]	3.3	58 [0, 170]	159 (7.1)	0.99 [0.98, 1.00]	5.1	59 [0-173]	162 (10)	0.97 [0.93, 0.99]	3.4	1.0 [0.0-3.1]	2.9 (9.2)
DL Standing PF	18	0.99 [0.96, 0.99]	3.3	80 [0, 236]	221 (9.3)	0.98 [0.95, 0.99]	4.8	82 [0-241]	226 (13)	0.96 [0.90, 0.98]	3.4	1.2 [0.0-3.5]	3.3 (9.8)
SL Standing PF	18	0.98 [0.96, 0.99]	3.0	55 [0, 163]	152 (8.2)	0.97 [0.93, 0.99]	4.9	56 [0-166]	156 (13)	0.96 [0.89, 0.98]	3.0	0.8 [0.0-2.3]	2.1 (8.0)
DL Seated PF	18	0.97 [0.92, 0.99]	4.8	100 [0, 295]	276 (14.5)	-	-	-	-	0.97 [0.92, 0.99]	4.8	1.2 [0.0-3.6]	3.4 (12.3)
SL Seated PF	18	0.97 [0.92, 0.99]	5.9	51 [0, 151]	141 (13.3)	-	-	-	-	0.95 [0.86, 0.98]	6.0	0.8 [0.0-2.3]	2.2 (14.3)

DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; ICC, Intraclass Correlation Coefficient; CV, Coefficient of Variation; SEM, Standard Error of Measurement; MDC, Minimal Detectable Change; vGRF, Vertical Ground Reaction Force; CI, Confidence Interval.

Table 5.3. Mean ± SD and 95% confidence intervals for peak and relative vertical ground reaction force

Position	**Sex**		**Absolute vGRF (N)**		**Net vGRF (N)**		**Relative vGRF (N·kg^{-1})**	
		n	**Mean ± SD**	**95% CI**	**Mean ± SD**	**95% CI**	**Mean ± SD**	**95% CI**
DL Squat	Female	9	1859 ± 65	1816–1902	1290 ± 65	1248–1333	32.0 ± 1.2	31.3–32.8
	Male	9	3485 ± 83	3430–3539	2677 ± 83	2622–2731	42.7 ± 1.0	42.1–43.4
SL Squat	Female	9	1588 ± 55	1552–1623	1019 ± 55	983–1055	27.4 ± 1.0	26.8–28.1
	Male	9	2909 ± 100	2844–2975	2101 ± 100	2036–2166	35.8 ± 1.2	35.1–36.6
DL Standing PF	Female	9	1813 ± 54	1778–1849	1245 ± 54	1209–1280	31.2 ± 0.9	30.6–31.9
	Male	9	2941 ± 165	2833–3048	2132 ± 165	2025–2240	36.3 ± 2.0	35.0–37.6
SL Standing PF	Female	9	1474 ± 51	1441–1508	905 ± 51	872–939	25.5 ± 0.9	24.9–26.1
	Male	9	2221 ± 68	2177–2265	1413 ± 68	1369–1457	27.3 ± 0.8	26.8–27.9
DL Seated PF	Female	9	1477 ± 65	1434–1520	-	-	25.7 ± 1.1	25.0–26.5
	Male	9	2334 ± 178	2218–2451	-	-	29.0 ± 2.2	27.5–30.4
SL Seated PF	Female	9	825 ± 44	797–854	-	-	14.3 ± 0.8	13.8–14.8
	Male	9	1294 ± 62	1254–1335	-	-	16.0 ± 0.7	15.5–16.5

DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; vGRF, Vertical Ground Reaction Force; CI, Confidence Interval.

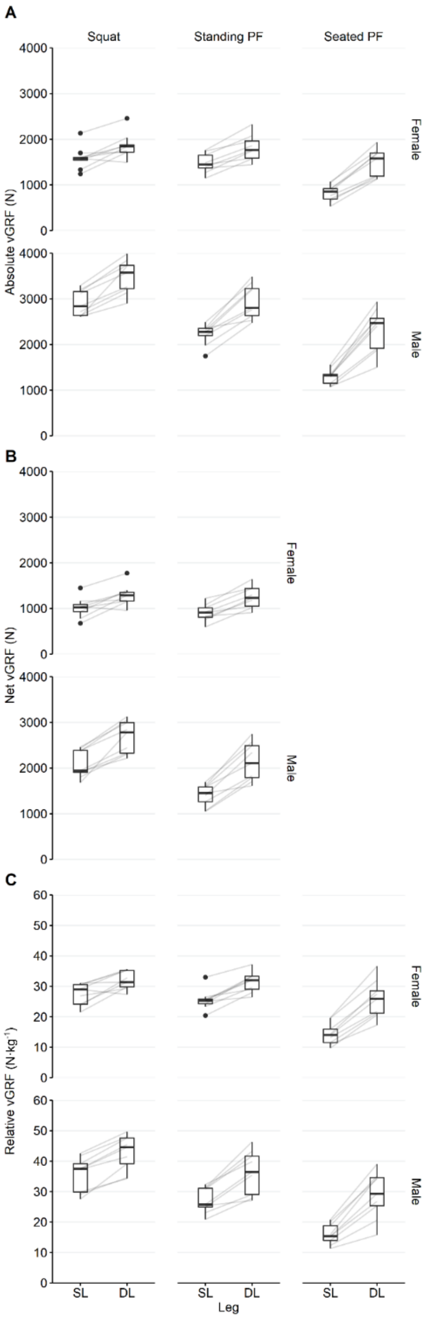


Figure 5.3 Box plots and individual differences in absolute A), net B), and relative C) vGRF between unilateral and bilateral test positions across the squat, standing plantarflexion, and seated plantarflexion. DL, Double-Leg; SL, Single-Leg; PF, Plantarflexion; vGRF, Vertical Ground Reaction Force.

5.5 Discussion

We examined the reliability, variability, and MDC of maximal isometric force tests across bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions. We found excellent within- and between-session reliability (ICC ≥ 0.92) and low variability (CV ≤ 6.5%) for absolute, net, and relative vGRF across all testing positions. This is the first study to investigate the reliability, variability, and MDC of the absolute, net, and relative vGRF during the unilateral squat and the bilateral and unilateral ankle plantarflexion positions during maximal isometric force tests.

The within-session reliability and variability of vGRF measures observed during the bilateral and unilateral squat in the present study are in line with previous research investigating these positions.[182,286,287] We observed excellent between-session reliability (ICC ≥ 0.99) and low between-session CVs (≤ 2.8%) during the isometric bilateral squat. Three prior studies have investigated the between-session reliability of absolute vGRF during the bilateral squat and reported ICC values greater than 0.85; two studies investigated men,[283,301] and one investigated women.[282] Only one study, however, used comparable equipment to the present investigation,[301] with the remaining two studies using hack squat machines.[282,283] We demonstrate excellent between-session reliability (ICC ≥ 0.95) of vGRF measures during the unilateral squat, and bilateral and unilateral variations of standing and seated plantarflexion positions. The unilateral squat and unilateral plantarflexion positions have been investigated previously, typically demonstrating ICCs greater than 0.90.[283,284,287] These studies, however, have used bespoke equipment, such as a wall-mounted force platform, that may not be practical in applied environments. Our findings demonstrate that maximal isometric force tests across bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions provide reliable measures of the absolute, net, and relative vGRF. Further, our findings support the notion that multiple test positions can be executed using a general isometric rig without the need for additional equipment.

The MDC for absolute vGRF ranged from 135 to 221 N (5.1–9.3% of the group mean) during bilateral and unilateral variations of the squat and standing plantarflexion positions. Previous research investigating the bilateral squat reported the MDC as 273 N (10.9%) and 230 N (~18.3%) in men and women, respectively.[282,301] Differences in study design may explain the ~100 N variation observed in the MDC between the present study and previous research. One study investigated larger knee angles using similar equipment,[301] and one investigated comparable knee angles with different equipment.[282] Based on the utility of a general isometric rig in applied practice, we encourage future research to use similar equipment to the present study to facilitate comparisons. The MDC for absolute vGRF was 276 N (14.5%) and 141 N (13.3%) during bilateral and unilateral variations of seated plantarflexion, respectively. The higher MDC values (relative to the mean) may be attributed to the bar placement on the distal thigh, as it results in localized pressure and several participants reported discomfort during the test. Future research might investigate other setups, such as the use of a bespoke bar and pad that more evenly distributes pressure across the thigh.

Applied practitioners may wish to consider the expected changes following a resistance training intervention when interpreting the MDC. Changes in isometric peak force during a mid-thigh pull following a 4-week traditional resistance training intervention have been reported as 7.7 ± 11.8% during moderate load (60–82.5% 1RM) and 3.8 ± 10.6% during high load (80–90% 1RM) protocols.[302] To the author's knowledge, there is limited literature reporting changes to plantarflexion peak force following a moderate- or high-force ankle-specific training intervention, with most interventions utilizing Therabands.[303] To that end, and in the absence of more research, the MDC values observed in the present study reflect realistic changes in lower extremity force production following a training intervention.

In the present study, absolute vGRF was typically greater in the non-dancers, however, relative vGRF was typically greater in the professional dancers. Greater relative strength in the professional ballet dancers likely reflects the training requirements associated with being a professional athlete. Across all men, absolute vGRF observed during the bilateral squat aligns with those reported in male Division 1 football and track and field athletes[304] and is ~500–1000 N greater than that of collegiate rugby union players, distance runners, and amateur boxers.[182] For all women, absolute vGRF observed during the bilateral squat was comparable to those reported across various sports [305]. Only two studies have investigated absolute vGRF during the unilateral squat, reporting values ~1000–1500 N lower than that observed in the present study.[284,286] Two studies have investigated plantarflexion with an extended knee; one reported similar values in recreational dancers[306] and one reported values two-thirds of that observed in the present study in recreational athletes.[284] Two studies have investigated absolute vGRF during unilateral seated plantarflexion[285,307] and reported values comparable to the present study. The aforementioned studies, however, tested seated plantarflexion in relative dorsiflexion (as opposed to a plantarflexed position), which is associated with optimal force production of the plantar flexors.[308] It should be noted that although this may be associated with optimal force production, placing a participant in dorsiflexion will require additional equipment, such as a calf raise block, to ensure the heel is not in contact with the ground.

We did not outline any formal hypothesises regarding the effect of bilateral or unilateral stance on vGRF, however, we have observed several interesting findings that may direct future research. We observed relatively small differences in vGRF between bilateral and unilateral variations of the isometric squat (men: 19.9%; women: 18.2%) and standing plantarflexion position (men: 32.6%; women: 23.4%) but not seated plantarflexion position (men: 79.3%; women: 80.3%). We speculate that the limited increase in vGRF during the bilateral standing positions—compared to their unilateral counterparts—may be due to the participants' ability to transmit force through the trunk. Larger differences in vGRF were observed between bilateral and unilateral variations of the seated plantarflexion position where the trunk is not loaded. To that end, we speculate that greater muscle mass in the trunk and upper body may moderate the transmission of force to the lower extremity and result in greater vGRF during the bilateral test [309,310]. Further research investigating differences in absolute vGRF between bilateral and unilateral variations of standing isometric force tests is warranted.

5.5.1 Limitations

There are several limitations to this study, for example, there may have been fatigue or potentiation effects as the order in which isometric force tests were completed was not randomized. Tests were ordered to start with the highest vGRF and finish with the lowest vGRF (e.g., bilateral squat first and unilateral seated plantarflexion last). The internal training load 48 h prior to testing was significantly different between the two sessions. The between-session reliability and variability, however, were excellent, suggesting that these tests are robust to acute changes in internal training load. This supports previous findings suggesting that vGRF measures during the mid-thigh pull are appropriate for period monitoring, but may not be sensitive to detect acute changes in neuromuscular fatigue.[311] The left limb was not tested, nor was limb dominance established, which may have revealed additional insights into the reliability associated with limb dominance.[312] Previous research has demonstrated differences in vGRF between dominant and non-dominant limbs during the unilateral squat, however, the effect size was small with differences in reported values of ~70 N.[287] The relatively short rest periods of 20 s may be perceived as a potential limitation as previous research has investigated longer rest periods between repetitions (e.g., ≥ 60 s).[305] Nonetheless, within-session reliability was excellent, suggesting that isometric force testing is robust to short inter-repetition rest potentially due to the low metabolic cost of isometric contractions.[313] The foam pad may have resulted in some joint motion, however, the lead investigator measured joint angles during sub-maximal contractions to minimise potential angle changes during maximal trials. Finally, the smallest possible vertical increment of the isometric rig was 2.5 cm, limiting the precise individual adjustment of bar height.

5.5.2 Practical Applications

This study demonstrates that bilateral and unilateral variations of the squat, standing plantarflexion, and seated plantarflexion positions provide reliable measures of the absolute, net, and relative vGRF. For simplicity, practitioners may wish to utilise one measure of vGRF in practice due to comparable reliability and variability across absolute, net, and relative vGRF. We observed similarities in vGRF between bilateral and unilateral variations of the isometric squat and standing plantarflexion positions. We speculate that bilateral variations of axially loaded tests may not reflect the true strength characteristics of the lower extremity and might be limited by the participants' ability to transmit higher forces through the trunk. The unilateral squat may therefore be a preferable test when aiming to measure lower extremity strength. Conversely, where an athlete's ability to transmit high forces through the entire kinetic chain in a bilateral stance is of interest, the inclusion of the bilateral squat in a testing battery is warranted. This study provides reference absolute, net, and relative vGRF data for men and women, alongside the MDC, which can facilitate criteria-based decision-making in applied environments.

5.6 Conclusion

This is the first study to investigate the within- and between-session reliability, variability, and the MDC of vGRF measures during bilateral and unilateral variations of the isometric squat, standing plantarflexion, and seated plantarflexion positions. All test positions demonstrated excellent within- and between-session reliability alongside low variability. The maximal isometric force tests investigated in the present study are a time-effective option to measure lower extremity vGRF using only a general isometric rig and force platform. Further, when interpreting a meaningful change, absolute vGRF values between 135–221 N (5.1 to 9.3% of the group mean) in standing and 141–276 N (13.3–14.5% of the group mean) in sitting can be used as benchmarks.

CHAPTER 6

Reliability of Ankle Mechanics During Jump Landings in Turned-Out and Parallel Foot Positions in Professional Ballet Dancers

6.1 Abstract

Objective To determine the within- and between-session reliability of ankle mechanics and vGRF during jump landings in turned-out and parallel foot positions in professional ballet dancers.

Methods Twenty-four professional ballet dancers (men = 13, women = 11) attended two data collection sessions where they completed five maximal countermovement jumps in each foot position. The ankle joint mechanics and vGRF of the right limb were recorded via a seven-camera motion capture system and one force platform. Within- and between-session ICC, CV, standard error of measurement, and minimal detectable change were calculated for three-dimensional ankle excursion, peak ankle angle, ankle joint velocity, moment, and power, as well as peak landing vGRF, time to peak landing vGRF, loading rate, and jump height.

Results Across both foot positions, within- (ICC: 0.17–0.96; CV: 1.4–82.3%) and between-session (ICC: 0.02–0.98; CV:1.3–57.1%) reliability ranged from *poor* to *excellent*, with ankle excursion, peak ankle angle, and jump height demonstrating the greatest ICC values (ICC: 0.65–0.96; CV: 1.4–57%).

Conclusion Jump landings in a turned-out foot position demonstrated better within-session reliability compared to a parallel position, however, no difference in between-session reliability across the foot positions was observed. Most ankle mechanics provide adequate between-session, but not within-session, reliability during jump landings in professional ballet dancers.

6.2 Introduction

High rates of jumping are observed during a performance in professional ballet compared to other dance genres.[10] It is perhaps unsurprising, therefore, that jumping and landing activities have been identified as a common mechanism of injury in professional ballet dancers, accounting for 27% and 38% of all time-loss injuries in women and men, respectively.[314] Further, the foot and ankle demonstrate the greatest burden of injury in professional ballet dancers compared to all other anatomical locations,[314] and thus ankle biomechanics during jumping and landing actions are of interest to science and medicine practitioners working in ballet.[83]

Ballet-specific jumping is unique and investigating jumping actions in balletic positions may offer a more ecologically valid insight into biomechanics compared to traditional jumping (i.e., jumping with feet in parallel). For example, several articles have investigated jumping actions in ballet dancers and identified a more upright torso, greater external rotation of the lower limb, and an increased contribution of ankle joint mechanics during a *sauté* (a jump with externally rotated lower limbs) compared to a neutral foot position.[80,109] Similar considerations are present in sport, and, when investigated, sport-specific jumps are typically less reliable than traditional jumps.[315–317] Ballet, however, is an aesthetic art and the reproducibility of technique is a key performance indicator, potentially increasing the reliability of ballet-specific jumps.

Understanding the reliability of kinetic and kinematic variables, derived from ecologically valid jumping actions, is critical when interpreting the results of both cross-sectional and longitudinal research in professional ballet.[292,315] Further, establishing the MDC of these variables may provide researchers and applied practitioners with tangible information pertaining to the success of an intervention.[292] No published data exist that have investigated the reliability of joint mechanics or vGRF during ballet-specific jump landings. The aim of this study was to establish the within- and between-session reliability of ankle joint mechanics and vGRF during jump landings in a turned-out and parallel foot position.

6.3 Methods

6.3.1 Study Design

A within-subject test-retest design was employed to investigate the reliability of ankle joint mechanics and vGRFs during jump landings in a turned-out (i.e., externally rotated lower extremity) and a parallel foot position in professional ballet dancers (Figure 6.1). *A priori* power analysis revealed a minimum of two replicants and 9 participants were required to calculate ICC ($\alpha = 0.05$, $\beta = 0.80$) based on an expected reliability (ρ_1) ≥ 0.9[318] and an acceptable reliability (ρ_0) ≥ 0.5.[293,294] Participants attended two data collection sessions—separated by 6.3 ± 3.1 days—in which five jumps in a turned-out and five jumps in parallel foot position were completed. Internal training load was calculated for the 48 hours preceding testing using the session rating of perceived exertion method for each participant.[295] All testing was conducted in the Royal Opera House, London.

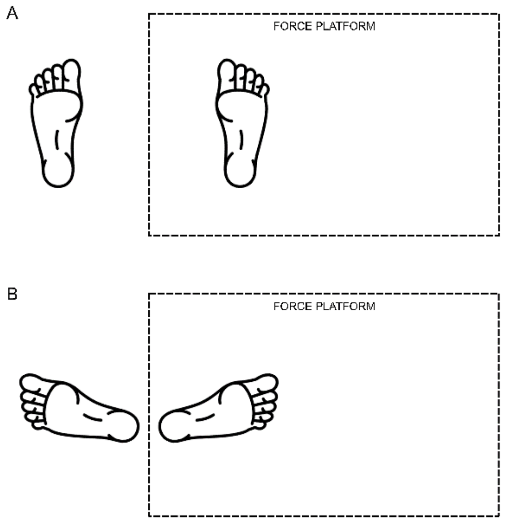


Figure 6.1 (A) Parallel foot position with reference to force platform; (B) Turned-out foot position with reference to force platform.

6.3.2 Participants

A sample of 24 professional ballet dancers (men: *n* = 13, age: 26.8 ± 5.1 y, height: 1.79 ± 0.04 m, mass: 73.0 ± 5.2 kg; women: *n* = 11, age: 24.3 ± 3.6 y, height: 1.68 ±

0.04 m, mass: 55.2 ± 3.6 kg) volunteered to participate in this study. Participants were required to have been free from a lower extremity time-loss injury in the six weeks prior to testing. Ethical approval was granted by St Mary's University in accordance with the Declaration of Helsinki and informed consent was provided by all participants prior to data collection.

6.3.3 Procedure

Participants completed a standardised and progressive warm-up prior to testing. Retroreflective markers (22 mm diameter) were attached to the right: greater trochanter, medial and lateral joint lines of the knee, medial and lateral malleolus, posterior aspect of the calcaneus, superior aspect of the navicular, medial aspect of the 1st metatarsal head, and the lateral aspect of the 5th metatarsal head. Curved rigid moulded clusters with four retroreflective markers were attached to the lateral aspect of the right shank (Figure 6.2).

Participants completed five maximal bilateral CMJ in a turned-out and parallel foot position, where foot position was maintained during take-off and landing. The right limb was positioned on the force platform and the left limb was positioned on a wooden frame that surrounded the force platform (Figure 6.1). The participants were instructed to place their hands on their shoulders during CMJs. Order effects were mitigated by counterbalancing CMJs in a turned-out and parallel foot position until five CMJs were performed in each position. Twenty seconds of rest was provided between each CMJ.[319]

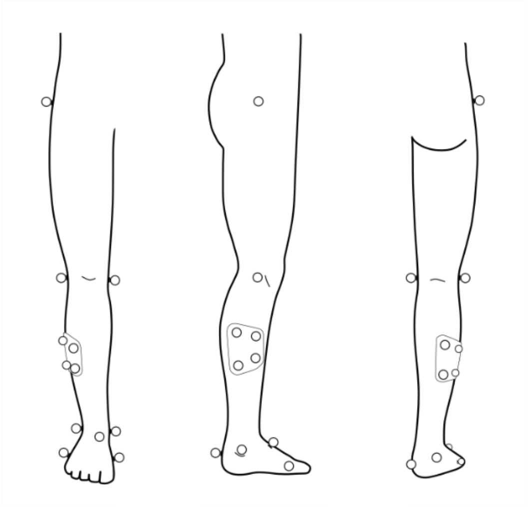


Figure 6.2 Marker placement on the right limb from the anterior, lateral, and posterior aspects.

6.3.4 Data Collection

A seven-camera motion capture system (MX3/MX3+, Vicon Motion Systems Ltd, Oxford, United Kingdom) sampling at 200 Hz, and one piezoelectric force platform (9268A, Kistler, Winterthur, Switzerland) sampling at 1000 Hz synchronously recorded retroreflective marker coordinates and ground reaction forces, respectively.

6.3.5 Data Analysis

Marker trajectories were reconstructed and tagged in Vicon Nexus (Vicon Motion Systems Ltd, Oxford, United Kingdom) before being processed in Visual 3D (v2021.113 C-Motion©, USA). All marker trajectory gaps consisted of seven frames or fewer and were interpolated using cubic splines. A foot and a shank segment were created to calculate ankle mechanics. The foot segment was defined by the posterior aspect of the calcaneus as the proximal endpoint and the medial aspect of the 1st metatarsal head and the lateral aspect of the 5th metatarsal head as the distal endpoints. The shank segment was defined by the medial and lateral joint lines of the knee as the proximal endpoints and the medial and lateral malleolus as the distal endpoints. All markers were used to track segments during dynamic trials.

Table 6.1 Target variables

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

An inverse kinematics approach was used to estimate the pose of the segments,[320] filtered at 8 Hz and allowing three degrees of rotation but no translation between the foot and shank segments. A full list of calculated variables can be found in Table 6.1. Ankle joint angles were calculated using an XYZ Cardan rotation sequence whilst the proximal segment was used as both the reference segment and the resolution coordinate system when determining ankle angular velocity. Kinematic data and segmental inertial data were combined with ground reaction force data to calculate joint kinetics using an inverse dynamics approach.[321] Marker and ground reaction force data were filtered at 8 Hz using a low pass fourth-order Butterworth filter, determined via residual analysis.[322] Ankle joint moment and joint power were normalised[323]—leg length was replaced with height[324] and an adjusted calculation for normalized power was used[325] as follows:

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

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

The vGRF data were reprocessed and filtered at 250 Hz using a low pass fourth-order Butterworth filter, determined via residual analysis,[322] to calculate normalised landing vGRF:

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

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

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

Jump height was calculated as the difference between the height of the greater trochanter in standing and at the peak of flight using the raw marker coordinates.

6.3.6 Statistical Analysis

Two-way mixed-effects models were used to calculate ICCs, with 95% confidence intervals, for within- (ICC: 2, k) and between-session (ICC: 2,1) reliability across all variables and positions using the *irr* R package.[297] The within-session reliability was calculated across the five trials of the first session whereas between-session reliability was calculated using the mean of the five trials. The ICC was interpreted in line with Koo and Li[293] where < 0.50 was considered *poor*; 0.50–0.75 was considered *moderate*; 0.75–0.90 was considered *good*; > 0.90 was considered *excellent*. The within- and between-session CV was calculated using the *EnvStats* R package.[298] Standard error of measurement (SEM) was calculated using the following equation:

$$SEM = SD_{baseline}\sqrt{1 - ICC_{between}}$$

Where $SD_{baseline}$ was considered the between-subject standard deviation (SD) of each variable during the first testing session, and $ICC_{between}$ was considered the between-session ICC.[299] The MDC was calculated using the following equation:[299]

$$MDC = 1.96 \times \sqrt{2} \times SEM$$

A paired samples t-test was used to investigate differences in the mean internal training load between sessions using the *stats* R package.[300] All analyses were conducted using R (version 4.2.1, R Foundation for Statistical Computing, Vienna, Austria).

6.4 Results

Data from 23 dancers were included for within-session ICCs during jump landings in a turned-out foot position, as only four were successfully processed for one dancer during the first testing session. No differences in internal training load prior to the first (mean ± SD: 1389 ± 660, range: 150–2872 arbitrary units) and second (mean ± SD: 1473 ± 783, range: 90–2772 arbitrary units) data collection sessions were observed ($t = -0.53$, $p = .604$).

Within-session reliability ranged from *poor* to *excellent*, with ICC values between 0.17–0.96 during jump landings in parallel and 0.20–0.96 during jump landings in a turned-out position (Table 6.2). Peak vGRF, time to peak vGRF, loading rate and peak transverse plane ankle joint velocity and power demonstrate the lowest within-session reliability across both jump conditions (ICC: 0.17–0.48), whereas jump height, and peak ankle angle and ankle excursion through all planes demonstrated the greatest within-session reliability (ICC: 0.65–0.96). The between-session reliability ranged from *poor* to *excellent*, with ICC values between 0.14–0.98 during jump landings in parallel and 0.02–0.98 during jump landings in turnout (Table 6.3, Figure 6.3, and Figure 6.4). Peak ankle velocity in the frontal and transverse plane demonstrated the lowest between-session reliability across both jump conditions (ICC: 0.02–0.43), whereas jump height, and peak ankle angle and ankle excursion through all planes demonstrated the greatest between-session reliability (ICC: 0.67–0.98). Notable between-participant variability was observed during jump landings in both turned-out and parallel foot positions (Figures 6.3 and 6.4), which may have impacted the MDC (Table 6.3). Sagittal plane MDC values were generally the lowest when compared to frontal and transverse plane MDC values (1.2–23.2% vs. 8.8–142.2% of the group mean). No substantial difference was observed between MDC values in turned-out and parallel foot positions (Table 6.3).

Table 6.2 The within-session interclass correlation coefficient and coefficient of variation across jumps in parallel and turnout.

Outcome Variable	Parallel			Turnout		
	n	ICC [95% CI]	CV (%)	*n*	ICC [95% CI]	CV (%)
Peak Ankle Moment ($\mathrm{Nm \cdot kg \cdot m^{-1}}$)						
Sagittal	24	0.40 [0.21, 0.61]	9.7	23	0.66 [0.50, 0.81]	9.6
Frontal	24	0.35 [0.17, 0.57]	54.1	23	0.26 [0.09, 0.49]	82.3
Transverse	24	0.46 [0.27, 0.66]	56.8	23	0.46 [0.27, 0.67]	66.6
Peak Ankle Power ($\mathrm{W \cdot kg \cdot m^{-1}}$)						
Sagittal	24	0.32 [0.15, 0.54]	15.5	23	0.64 [0.47, 0.80]	11.9
Frontal	24	0.67 [0.51, 0.82]	32.4	23	0.76 [0.62, 0.87]	24.9
Transverse	24	0.28 [0.11, 0.51]	31.8	23	0.48 [0.29, 0.68]	31.8
Peak Ankle Velocity ($\mathrm{° \cdot s^{-1}}$)						
Sagittal	24	0.41 [0.24, 0.62]	7.7	23	0.58 [0.39, 0.76]	5.8
Frontal	24	0.42 [0.24, 0.63]	46.2	23	0.40 [0.22, 0.62]	48.6
Transverse	24	0.21 [0.05, 0.43]	42.4	23	0.43 [0.25, 0.65]	36.7
Peak Ankle Angle (°)						
Sagittal	24	0.87 [0.77, 0.93]	1.4	23	0.89 [0.81, 0.94]	1.5
Frontal	24	0.65 [0.49, 0.80]	52.8	23	0.74 [0.60, 0.86]	51.8
Transverse	24	0.89 [0.81, 0.94]	27.9	23	0.87 [0.78, 0.93]	46.3
Ankle Excursion (°)						
Sagittal	24	0.74 [0.60, 0.86]	5.0	24	0.80 [0.67-0.89]	3.4
Frontal	24	0.66 [0.50, 0.81]	11.3	24	0.77 [0.63-0.88]	9.5
Transverse	24	0.78 [0.65, 0.88]	18.6	24	0.81 [0.70-0.90]	15.3
Peak Landing vGRF (BW)	24	0.17 [0.03, 0.39]	26.1	23	0.44 [0.25, 0.65]	23.4
TTP Peak Landing vGRF (s)	24	0.37 [0.19, 0.58]	20.4	23	0.21 [0.05, 0.44]	23.7
Loading Rate ($\mathrm{BW \cdot s^{-1}}$)	24	0.20 [0.05, 0.41]	45.6	23	0.20 [0.04, 0.43]	50.5
Jump Height (cm)	24	0.96 [0.93, 0.98]	3.6	23	0.96 [0.93, 0.98]	3.4

ICC, interclass correlation coefficient; CV, coefficient of variation; vGRF, vertical ground reaction force; TTP, time to peak

Table 6.3 The between-session interclass correlation coefficient, coefficient of variation, standard error of measurement, and minimal detectable change across jumps in parallel and turnout.

Outcome Variable	*n*	Parallel				Turnout			
		ICC [95% CI]	CV	SEM [95% CI]	MDC (%)	ICC [95% CI]	CV	SEM [95% CI]	MDC (%)
Peak Ankle Moment (Nm·kg·h^{-1})									
Sagittal	24	0.68 [0.25, 0.86]	5.9	0.005 [0.000, 0.016]	0.015 (15.2)	0.79 [0.52, 0.91]	5.6	0.004 [0.000, 0.012]	0.011 (12.0)
Frontal	24	0.83 [0.60, 0.93]	24.5	0.004 [0.000, 0.012]	0.011 (59.0)	0.82 [0.60, 0.92]	57.1	0.004 [0.000, 0.011]	0.010 (103.8)
Transverse	24	0.53 [0.00, 0.80]	35.3	0.004 [0.000, 0.012]	0.011 (102.6)	0.61 [0.10, 0.83]	39.4	0.002 [0.000, 0.005]	0.005 (102.6)
Peak Ankle Power (W·kg·h^{-1})									
Sagittal	24	0.70 [0.31, 0.87]	8.5	0.10 [0.00, 0.30]	0.28 (23.2)	0.75 [0.40, 0.89]	8.6	0.07 [0.00, 0.22]	0.20 (16.0)
Frontal	24	0.66 [0.23, 0.85]	28.1	0.02 [0.00, 0.06]	0.05 (48.3)	0.62 [0.14, 0.83]	21.5	0.02 [0.00, 0.07]	0.06 (39.8)
Transverse	24	0.72 [0.35, 0.88]	21.3	0.01 [0.00, 0.04]	0.04 (46.6)	0.65 [0.20, 0.85]	20.7	0.02 [0.00, 0.05]	0.05 (51.4)
Peak Ankle Velocity (°·s^{-1})									
Sagittal	24	0.64 [0.19, 0.84]	4.6	43 [0, 129]	120 (13.2)	0.70 [0.29, 0.87]	4.1	30 [0, 89]	83 (8.9)
Frontal	24	0.35 [0.00, 0.72]	31.2	36 [0, 106]	99 (100.8)	0.02 [0.00, 0.59]	28.5	42 [0, 124]	116 (128.1)
Transverse	24	0.14 [0.00, 0.63]	32.4	50 [0, 147]	138 (107.5)	0.43 [0.00, 0.75]	22.7	42 [0, 125]	117 (73.0)
Peak Ankle Angle (°)									
Sagittal	24	0.91 [0.80, 0.96]	1.3	0.4 [0.0, 1.3]	1.2 (1.2)	0.89 [0.75, 0.95]	1.3	0.5 [0.0, 1.5]	1.4 (1.3)
Frontal	24	0.67 [0.22, 0.86]	57	1.2 [0.0, 3.5]	3.2 (142.2)	0.79 [0.47, 0.91]	38.9	0.9 [0.0, 2.6]	2.4 (105.4)
Transverse	24	0.89 [0.75, 0.95]	28.1	0.6 [0.0, 1.7]	1.6 (20.6)	0.89 [0.74, 0.95]	46	0.7 [0.0, 2.0]	1.9 (52.2)
Ankle Excursion (°)									
Sagittal	24	0.87 [0.70, 0.94]	4	1.1 [0.0, 3.3]	3.1 (5.0)	0.86 [0.68, 0.94]	3.2	0.9 [0.0, 2.5]	2.4 (3.5)
Frontal	24	0.81 [0.56, 0.92]	8.2	1.0 [0.0, 2.9]	2.7 (13.0)	0.88 [0.71, 0.95]	6.8	0.7 [0.0, 2.1]	2.0 (8.8)
Transverse	24	0.75 [0.42, 0.89]	17.4	1.0 [0.0, 2.9]	2.7 (24.2)	0.80 [0.54, 0.91]	15.1	1.1 [0.0, 3.2]	3.0 (18.4)
Peak vGRF (BW)	24	0.71 [0.24, 0.88]	11.9	0.3 [0.0, 0.9]	0.8 [41.4]	0.69 [0.29, 0.87]	13.9	0.3 [0.0–0.8]	0.8 [37.7]
TTP Peak vGRF (s)	24	0.87 [0.70, 0.94]	8.7	0.006 [0.000, 0.018]	0.017 [19.0]	0.63 [0.18, 0.84]	16.9	0.012 [0.000–0.035]	0.032 [37.9]
Loading Rate (BW·s^{-1})	24	0.81 [0.57, 0.92]	18.4	6 [0, 17]	16 [60.0]	0.67 [0.24, 0.85]	31.2	10 [0–30]	28 [91.3]
Jump Height (cm)	24	0.98 [0.96, 0.99]	2.5	0.2 [0.0, 0.6]	0.6 [1.4]	0.98 [0.96, 0.99]	2.8	0.2 [0–0.6]	0.5 [1.3]

ICC, interclass correlation coefficient; CV, coefficient of variation; vGRF, vertical ground reaction force; SEM, standard error of measurement; MDC, smallest detectable change; TTP, time to peak

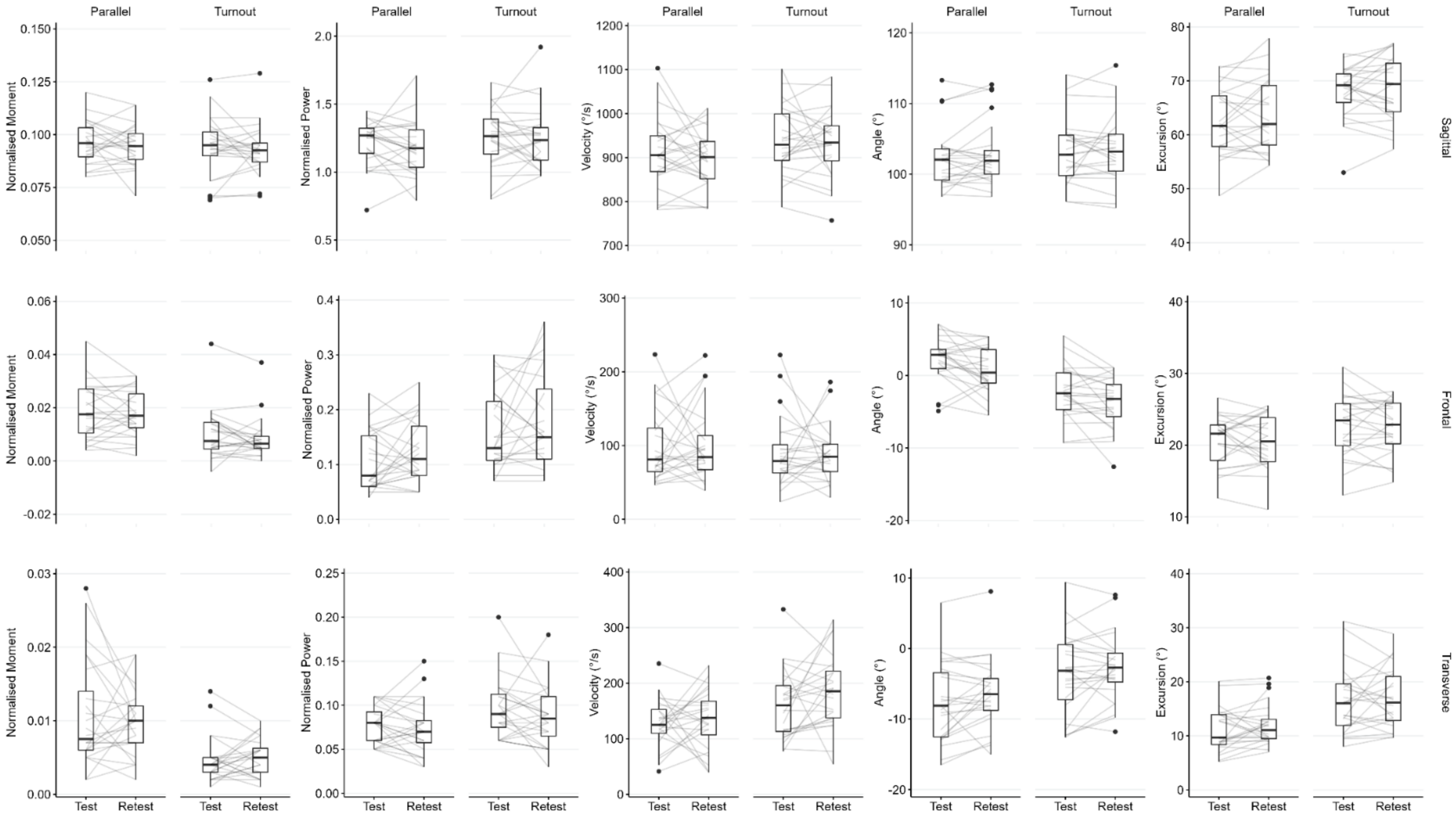


Figure 6.3. Box plots and individual test-retest values across ankle joint kinetic and kinematic variables during jumps in parallel and turnout. Black points indicate outliers.

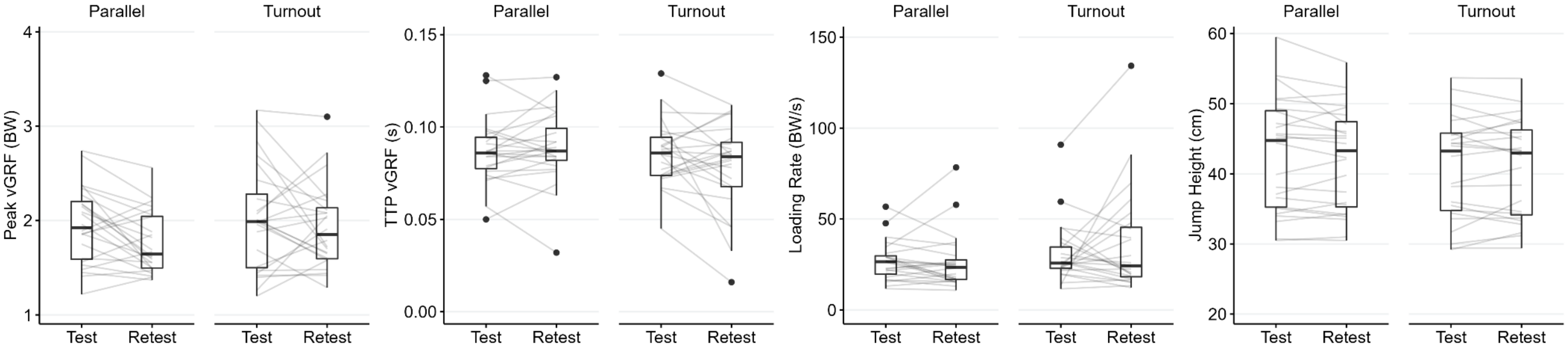


Figure 6.4. Box plots and individual test-retest values across vertical ground reaction force variables and jump height during jumps in parallel and turnout. Black points indicate outliers. TTP, Time to Peak; vGRF, vertical ground reaction force; BW, body weight

6.5 Discussion

The present study aimed to establish the within- and between-session reliability of ankle mechanics and vGRFs during jump landings in turned-out and parallel foot positions in professional ballet dancers. The between-session reliability was typically greater than the within-session reliability, which is contrary to previous findings investigating walking,[326] running,[327,328] and jumping.[318,329] Greater between-session reliability may be because the mean of multiple trials is used when calculating between-session ICCs, as opposed to individual trials in within-session ICCs.[330] Using the mean of multiple trials potentially provides a more accurate representation of the true value, however, it is not a unique feature of the present study, as most studies will process data in this manner.[331,332]

Lower within-session reliability was likely not a result of kinematic crosstalk[318] as *poor* reliability was observed across some, but not all, of the kinetic and kinematic outcome variables in the present study. Within-session reliability may have been influenced by skin artefact errors due to underlying muscular contractions or inertial effects upon impact.[333] Future work may wish to utilise rigid marker sets at the foot to minimize the effects of such errors. We speculate that the poorer within-session reliability observed in the present study may have been due to greater movement variability. Participants were instructed to jump maximally whereas both the aforementioned studies investigating jumping controlled for jump height by setting a target at 80% max jump height[330] or providing a box (31 cm) from which participants jumped.[318]

Between-session reliability was typically *moderate* to *good* with several exceptions, such as *poor* peak ankle velocity reliability in the frontal and transverse planes and *excellent* reliability across sagittal plane peak ankle angle. Few studies have reported the reliability of ankle joint velocity, making comparison challenging. Between-session ankle moment and angle ICCs were in line with previously reported values of *good* and *excellent* during landing activities,[318] although three of the six ankle moments in the sagittal and transverse planes were classified as *moderate* in the present study. No studies have reported the reliability of ankle power during landing activities, however, comparable values classified as *good* to *excellent* have been reported in running.[327] No previous work investigating biomechanics during jump landings has provided MDC values; nonetheless, our results indicate that most sagittal plane outcome variables require a smaller change to detect the success, or lack thereof, of an intervention when compared to frontal or transverse plane outcome variables.

Landing biomechanics were reliable across both ballet-specific and traditional jump landings in professional ballet dancers. Twelve of the nineteen within-session ICCs were greater during jump landings in a turned-out foot position compared to a parallel foot position, with three ICCs being equal. On the contrary, between-session ICCs were similar across jump landings in turned-out and parallel foot positions, with differences being negligible in many instances. Similarly, MDC values were largely the same between turned-out and parallel foot positions, with few exceptions. Ballet is an aesthetic performing art and success is subjectively quantified, in part, by the ability to reproduce technique. Thus, it may be expected that the variability from jump to jump may be better during ballet-specific jump landings compared to traditional jump landings.

Interpreting MDC values in line with expected changes can help applied practitioners identify a clinically meaningful change. Changes in sagittal, frontal, and transverse plane ankle joint angles of ~5–9°, ~1°, and ~1°, respectively, have been observed following a 6-week jumping intervention in male basketball players.[334] Our findings indicate that a change of 1.2° in the sagittal plane can be considered meaningful and realistic following a training intervention, however, larger changes of 1.6–3.2° would be required in the frontal and transverse plane, which may require longer or more specific interventions. Changes in vGRF may also require longer or more specific interventions to achieve a meaningful outcome, as the aforementioned hop intervention resulted in a change of 0.5 BWs,[334] compared to the MDC values in the present study of 0.8 BWs. To the authors' knowledge, no research has reported changes in ankle moments following a training intervention.

6.6 Conclusion

This is the first study to investigate the within- and between-session reliability of ankle mechanics and vGRF variables during jump landings in turned-out and parallel foot positions in professional ballet dancers. Most, but not all, ankle mechanics and vGRF outcome variables were deemed to be reliable, with between-session reliability better than within-session reliability. Jump height, peak ankle angle, and ankle excursions were considered the most reliable, however, all sagittal plane variables were deemed to be appropriate to use when assessing landing mechanics in ballet dancers. Further, this study has established the MDC of ankle mechanics and vGRF variables that can be used to determine the success of an intervention.

SECTION 3: JUMPING AND LANDING IN BALLET

CHAPTER 7

Ankle Mechanics During Jump Landings Across Different Foot Positions in Professional Ballet Dancers

7.1 Abstract

Objective To investigate the effect of sex and foot position on ankle joint mechanics and vGRF across jump landings in professional ballet dancers.

Methods Twenty-seven professional ballet dancers (men: 14; women: 13) attended one data collection session, completing five maximal countermovement jumps in parallel, first, second, fourth, and fifth positions. The ankle joint mechanics and vGRF of the right limb were recorded via a seven-camera motion capture system and one force platform. A repeated measures multivariate analysis of variance was used to assess the main effects of sex and foot position across three-dimensional ankle mechanics, landing vGRF variables, and jump height. A linear discriminate analysis was conducted to investigate how ankle mechanics and vGRF could discriminate different foot positions.

Results No sex differences were observed. Frontal and transverse plane kinetics and kinematics had the largest impact when discriminating between different foot positions, with jump landings in fourth and fifth positions demonstrating greater peak angles and excursions when compared to other foot positions. Ankle power in the transverse plane during jump landing in fourth position was double that of all other positions.

Conclusion The absence of sex differences may indicate the benefits of early adoption of jump and balance training. Our findings suggest that full ankle range of motion should be restored prior to returning to fourth and fifth positions following distal lower extremity injury. The differences in multiplanar kinetics potentially indicate a need for specific exercises to develop multiplanar force and rate of force development of local structures.

7.2 Introduction

The rehearsal and performance demands of professional ballet are characterised by a high volume of jumping actions.[3] Jumping actions have been associated with a third of all medical attention and time-loss injuries in professional ballet dancers;[314] with the greatest burden observed around the distal lower extremity. Moran et al.[83] suggested that jump volume and landing biomechanics may provide practitioners with the next great injury analytic for activities that have high jumping demands. Indeed, investigations into landing biomechanics will provide insights into the load experienced by different structures of the lower extremity in ballet dancers. Once the load experienced during landing is understood, practitioners can better manage the load-capacity relationship in hope of mitigating potential injury risk and maximising performance in ballet dancers.[87]

The technical requirements of ballet change the kinetic and kinematic characteristics of jumping.[335] For example, kinematic differences such as minimal hip flexion, an upright torso, and an externally rotated lower limb were observed when jumps in turn out were compared to jumps in parallel.[80] Further, an extended lower limb at initial contact and large sagittal plane lower limb excursions were observed when ballet dancers were compared to non-dancers.[254,256] Kinetic variables, such as lower extremity joint moment, power, and work have exhibited a proximal-to-distal shift in joint contributions during ballet-specific jumps compared to traditional jumps.[80,109] All of these characteristics are indicative of greater contributions from the distal lower extremities during jumping actions in ballet dancers, placing a greater demand on the tissues around the foot and ankle.[242] Two of the aforementioned studies focused their analysis on the take-off phase,[80,109] whilst the two studies that focused on the landing described differences in lower limb kinematics during non-ballet jumps between dancers and non-dancers.[254,256] Presently there is a lack of data pertaining to distal lower extremity joint mechanics during the landing phase of different ballet jumps.

There is a vast repertoire of jumps to which ballet dancers will be exposed each day, making the documentation of all of them challenging. Different ballet jumps may be characterised by whether they are travelling or stationary; have contributions from a single limb or both limbs; and whether there are technical actions throughout the different phases of the jump (such as beats, splits, or arabesques).[335] There are, however, codified foot positions that underpin all ballet technique, referred to as first, second, third, fourth, and fifth positions. All jumping actions will take off or land in one of these fundamental foot positions. Peak landing vGRF has been the most commonly reported variable across research investigating landing in ballet dancers.[335] The range in peak landing vGRF is between 1.4–9.6 times BW during various unilateral and bilateral ballet-specific jumps.[243–245,248,250,258] The technical requirements of the jump may influence the peak landing vGRF, as ballet-specific jumps tend to result in greater vGRF than traditional jumps.[335] It should be noted, however, two of these studies included sample sizes of one and two participants, which may not be generalisable to all dancers.[243,244] Loading rate has also been described during several ballet-specific jumps, with values ranging between 10–223 BW·s^{-1},[240,243,244,248,250], however, similar to the vGRF data, two of these studies had very small sample sizes and may not be generalizable.[243,244]

Much of the existing literature investigating jumping and landing in ballet dancers may not apply to elite populations as it has largely been conducted on non-professional or non-ballet populations.[335] Further, most literature has focused on female dancers, with limited exploration of potential sex differences in landing kinetics and kinematics.[335] Extensive research has identified sex differences across biomechanics during landing between men and women in a sporting context,[336] however, comparisons in a dance context are scant. The aim of this study was to investigate the effect of sex and foot position (parallel, first, second, fourth, and fifth) on ankle joint mechanics and vGRFs across jump landings in professional ballet dancers.

7.3 Methods

7.3.1 Study Design

A cross-sectional study design was employed to investigate the effect of sex and foot position on ankle mechanics and vGRF during jump landing in professional ballet dancers. Dancers attended one data collection session where they completed five CMJs across seven different foot positions (Figure 7.1). An *a priori* power analysis revealed that a minimum of 168 samples were required to calculate the main effects of a repeated measures multivariate analysis of variance (MANOVA; $\alpha = 0.05$, $\beta = 0.80$, Pillai V = 0.4), based on 14 groups (2 sexes × 7 foot positions) and 19 response variables (Table 7.1).[337] To that end, a minimum of 12 men and 12 women were required to complete jump landings in each of the seven foot positions such that 168 samples were recorded. All testing was conducted in the Royal Opera House.

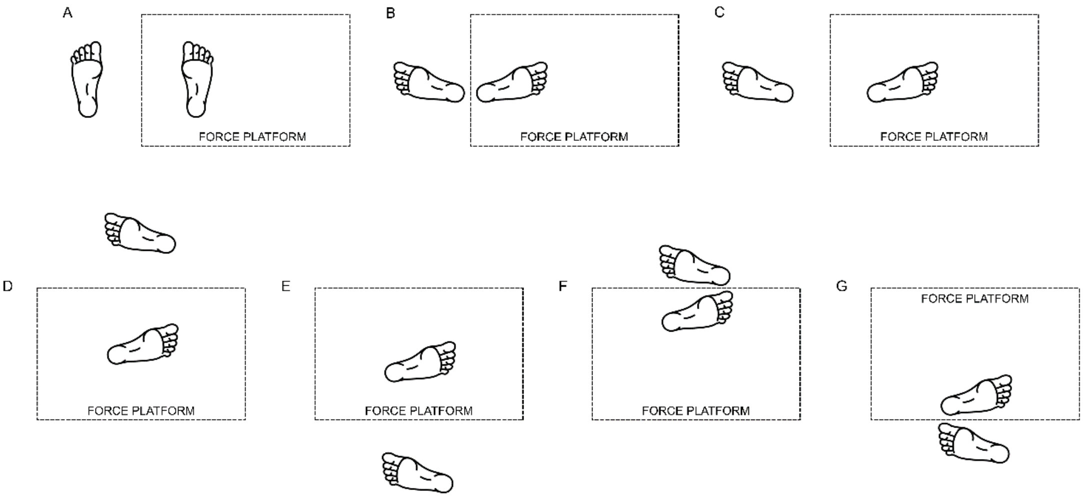


Figure 7.1. The foot positions tested in the present study with reference to the force platform. (A) parallel, (B) first, (C) second, (D) fourth back, (E) fourth front, (F) fifth back, (G) fifth front.

7.3.2 Participants

A total of 27 professional ballet dancers (men: *n* = 14, age: 26.7 ± 4.9 y, height: 1.79 ± 0.04 m, mass: 72.6 ± 5.2 kg; women: *n* = 13, age: 24.0 ± 3.7 y, height: 1.68 ± 0.04 m, mass: 55.2 ± 3.3 kg) volunteered to participate in this study. As such, 189 samples were included in the analysis (27 participants × 7 foot positions). Dancer ranks included Apprentices (*n* = 3), Artists (*n* = 8), First Artists (*n* = 6), Soloists (*n* = 2), First Soloists (*n* = 5), and Principals (*n* = 3). Participants were required to not have sustained a lower extremity time-loss injury in the six weeks prior to testing. Ethical approval was provided by St Mary’s University Ethics Committee in accordance with the Declaration of Helsinki.

7.3.3 Procedure

Participants completed a standardised and progressive warm-up prior to testing. Retroreflective markers (22 mm diameter) were attached to the right: greater trochanter, medial and lateral joint lines of the knee, medial and lateral malleolus, posterior aspect of the calcaneus, superior aspect of the navicular, medial aspect of the 1st metatarsal head, and the lateral aspect of the 5th metatarsal head using double-sided adhesive tape and adhesive spray. Curved rigid moulded clusters with four retroreflective markers were attached to the lateral aspect of the right shank using cohesive elastic tape and electrical tape (Figure 7.2).

Table 7.1 Target variables

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

Participants completed five maximal bilateral CMJs across seven different foot positions: parallel, first, second, fourth with the front leg on the force platform (fourth front), fourth position with the back leg on the force platform (fourth back), fifth position with the front leg on the force platform (fifth front), and fifth position with the back leg on the force platform (fifth back; Figure 7.1). The right limb was positioned on the force platform and the left limb was positioned on a wooden frame that surrounded the force platform (Figure 7.1). The participant's hands were placed on their shoulders for all jumps. Order effects were mitigated by alternating jumps until a jump in each foot position was performed within a set. Twenty seconds of intra-set rest and two minutes of inter-set rest were provided.[319]

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

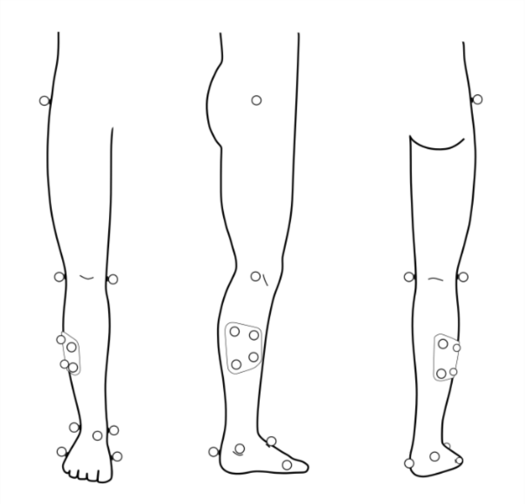


Figure 7.2. Marker placement on the right limb from the anterior, lateral, and posterior aspects.

7.3.4 Data Analysis

Marker trajectories were reconstructed and labelled in Vicon Nexus (Vicon Motion Systems Ltd, Oxford, United Kingdom) before being processed in Visual 3D (v2021.113 C-Motion©, USA). All marker trajectory gaps consisted of seven frames or fewer and were interpolated using cubic splines. A foot and a shank segment were created in Visual 3D. The foot was defined by the medial and lateral malleolus as the proximal endpoints and the medial aspect of the 1st metatarsal head and the lateral aspect of the 5th metatarsal head as the distal endpoints. The shank was defined by the medial and lateral joint lines of the knee as the proximal endpoints and the medial and lateral malleolus as the distal endpoints. Foot and shank segment inertia parameters were defined in line with de Leva.[321] Individual and cluster markers for the foot and shank were used to track segments during dynamic trials. An inverse kinematics approach was used to estimate the pose of the segments,[320] filtered at 8 Hz and allowing three degrees of rotation but no translation between the foot and shank segments. Ankle joint angles were calculated using an XYZ Cardan rotation sequence whilst the proximal segment was used as both the reference segment and the resolution coordinate system when determining ankle angular velocity. Kinematic data and segmental inertial data were combined with ground reaction force data to calculate joint kinetics using an inverse dynamics approach.[321] Marker and ground reaction force data were filtered at 8 Hz using a low-pass fourth-order Butterworth filter, determined via residual analysis.[322] Ankle joint moment and joint power were normalised for comparisons between participants[323]—leg length was replaced with height[324] and an adjusted calculation for normalized power was used to provide a dimensionless value:[325]

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

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

Vertical ground reaction force data were reprocessed and filtered at 250 Hz using a low pass fourth-order Butterworth filter, determined via residual analysis,[322] to calculate normalised peak landing vGRF, time to normalised peak landing vGRF, and loading rate:

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

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

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

7.3.5 Statistical Analysis

A repeated measures MANOVA was conducted to identify the between-subjects main effect of sex and foot position, and the within-subject main effect of foot position on ankle mechanics and vGRF during jump landings in professional ballet dancers using the R package *stats*.[300] Extreme outliers were removed (n = 22; 0.8%). The assumption of multivariate normality was violated and thus ordered quantile transformations were applied to all dependent variables using the R package *bestNormalize*.[338] A parametric approach was selected over a non-parametric approach as a MANOVA is robust to type 1 error and power decrements, and outperforms non-parametric equivalents in the presence of non-normal data.[339] Linear discriminate analyses (LDA) were conducted to investigate significant main effects using the R package *MASS*.[340] The LDA provides regression equations in which the contributions of all kinetic and kinematic outcome variables can be used to classify the main effect grouping variable (i.e., foot position). One additional post-hoc LDA was conducted based on visual inspection of the results from the initial LDA, where a hypothesis on how model accuracy may be improved was acted on.[341] The alpha level was set at $p \leq .001$ to account for the multiplicity of multiple outcome variables.[342] All data processing and statistical analysis were conducted using R (version 4.2.1, R Foundation for Statistical Computing, Vienna, Austria).

7.4 Results

The repeated measures MANOVA revealed no significant between-subject main effects of sex ($F_1 = 4.1$; $p = .212$; Pillai = 0.975) or foot position ($F_5 = 0.8$; $p = .834$; Pillai = 3.540). The repeated measures MANOVA, however, did reveal a significant within-subject main effect of foot position ($F_6 = 7.1$; $p < .001$; Pillai = 3.063).

One LDA was performed to investigate the main effect of foot position. Six linear discriminates were identified to classify foot position (LD1: 49.3%; LD2: 36.3%; LD3: 10.4%; LD4: 1.4%; LD5: 1.4%; LD6: 0.7%). The LDA investigating the effects of foot position had a prediction accuracy of 56.8% when tested for performance. Clear clusters were visually observed between the symmetrical ballet foot positions (first and second), positions assessing the back foot (fourth back and fifth back), and positions assessing the front foot (fourth front and fifth front) when plotted (Figure 7.3). Thus, a second LDA was conducted where these foot positions were grouped such that only four different foot positions were input into the model (i.e., parallel, first and second combined, fourth back and fifth back combined, and fourth front and fifth front combined). Three linear discriminates were identified to classify grouped foot positions (LD1: 51.4%; LD2: 43.0%; LD3: 5.5%). The LDA investigating the effects of grouped foot position had a prediction accuracy of 91.4% when tested for performance. The results of both models investigating the effect of foot position are presented in Figure 7.3. The regression equations representing the three linear discriminates for grouped foot positions can be found in Figure 7.4.

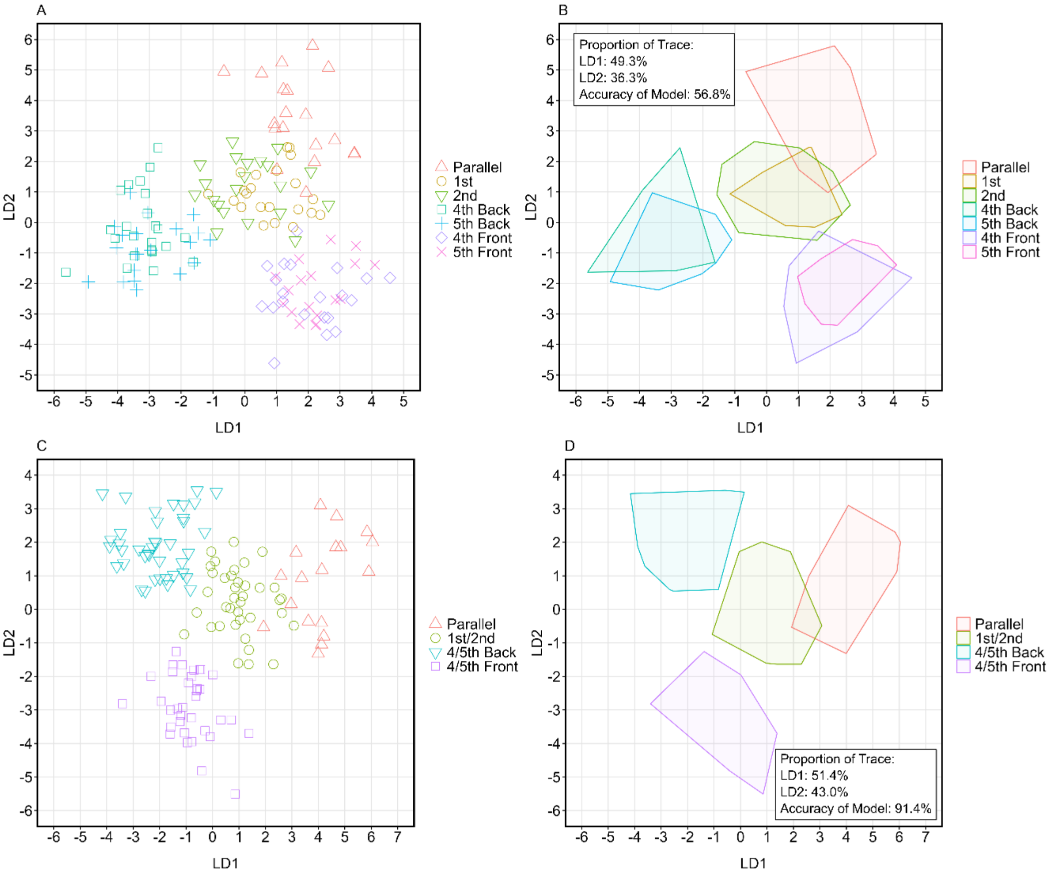
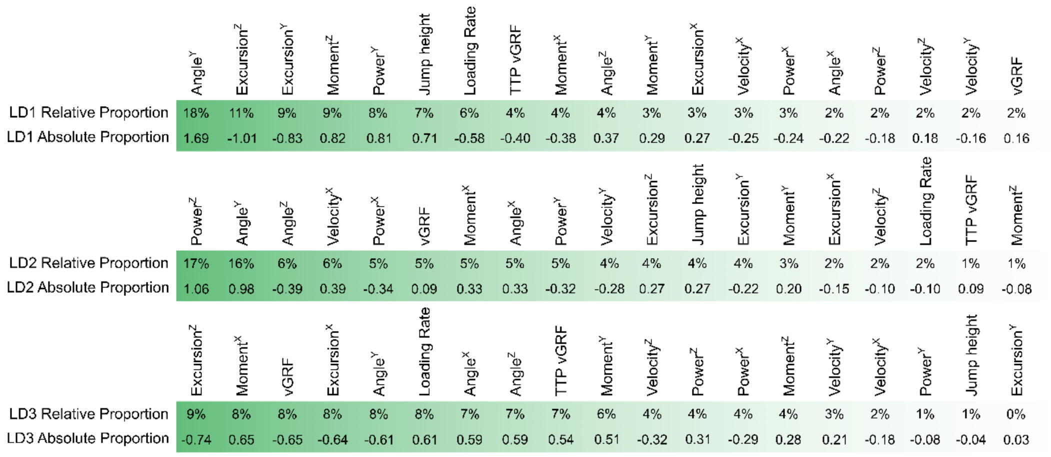


Figure 7.3. A) visualises the individual data and B) visualises the convex hull of the first linear discriminate analysis where seven individual foot positions were included. C) and D) show the results of the second linear discriminate analysis, where the seven foot positions were grouped following visual inspection.



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

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

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

Figure 7.4. The relative and absolute contributions of linear discriminants for grouped foot position. The Absolute proportion can be used as a regression equation to calculate the linear discriminate value from individual dancer data. The relative proportion provides an understanding of how each variable contributes to the linear discriminate value. Superscripts X, Y, and Z represent the sagittal, frontal, and transverse planes, respectively.

Table 7.2. Mean ± SD [95% CI] of ankle mechanics and vGRF across grouped foot positions

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

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

Table 7.3. Mean ± SD [95% CI] of ankle mechanics and vGRF across sex

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

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

Due to the relatively small contribution of LD3 (5.5%), only LD1 (51.4%) and LD2 (43.0%) are discussed in detail (Figure 7.4). Linear discriminate one was able to classify jump landings in parallel from all ballet-specific foot positions. Linear discriminate two was able to classify jump landings in the grouped front foot position from all other positions. Both fourth and fifth positions demonstrated a greater peak ankle abduction angle compared to all other foot positions, with the grouped front foot involving six times more abduction compared to first and second, and three times more abduction compared to the grouped back foot (Table 7.2). Frontal plane ankle excursions were greatest in the grouped front foot position, with values 15–20% larger than all other positions. Grouped first and second position exhibited transverse plane excursions 1.5 times that of parallel, and grouped front and grouped back foot positions exhibited transverse plane excursions twice that of parallel (Table 7.2).

Transverse plane ankle joint moments in parallel were at least twice that of all ballet foot positions. Conversely, frontal plane ankle joint power was 1.5 times greater in all ballet foot positions when compared to parallel. The grouped back foot peak ankle power in the transverse plane exhibited more than double that of all other foot positions. Jump height was comparable across all foot positions other than parallel where participants jumped an additional 3–4 cm (Table 7.2). Loading rate was typically 15% higher in grouped fourth and fifth positions compared to parallel and grouped first and second position. Differences in loading rate were largely due to higher vGRF in the asymmetrical positions as the time to peak force was comparable across all foot positions. Vertical ground reaction force was 6–8% greater in first and second and the grouped front foot position when compared to parallel and the grouped back foot position.

The mean, standard deviation, and 95% CI for all variables across the grouped foot positions are presented in Table 7.2. The mean, standard deviation, and 95% confidence intervals (95% CI) for all variables across men and women are presented in Table 7.3.

7.5 Discussion

This is the first study to investigate the effect of sex and foot position on ankle mechanics and vGRF in professional ballet dancers. The results demonstrated that foot position, but not sex, influences ankle mechanics and vGRF during jump landings in professional ballet dancers. Further, the results indicate that ankle mechanics and vGRFs are comparable between first and second positions, the back foot in both fourth and fifth positions, and the front foot in both fourth and fifth positions. In particular, the peak ankle joint angle in the frontal plane was able to discriminate between parallel and both grouped front and back foot positions. Peak transverse plane ankle power and frontal plane ankle joint angle were both able to discriminate between the grouped front foot and all other foot positions. These results highlight the biomechanical variance across these fundamental foot positions which may impact decision-making around technical and physical goal setting in professional ballet in a performance and rehabilitation context.

The absence of sex differences in ankle mechanics and vGRF is unsurprising given that most variables were normalised to either height, mass, or both. The only notable difference between men and women was jump height, where men jumped almost 1.5 times higher than their female counterparts. Previous literature investigating sex differences during various landing tasks in non-dance populations has found that women generally demonstrate greater joint angles and excursions when compared to men.[343] Much of this literature has focused on the knee and preventing anterior cruciate ligament injuries in female athletes,[336] however, joints of the lower extremity do not work in isolation and clear links between knee and ankle motion during landing have been demonstrated.[344] Previous literature on dance populations has identified findings consistent with the present study, where no differences were observed in knee kinematics or kinetics between male and female professional modern and ballet dancers.[116] Further, when dancers and athletes have been investigated, only female athletes demonstrated significantly different joint kinematics during jump landings when compared to male athletes and dancers of both sexes.[123] In line with Orishimo et al.[116] we speculate that the lack of differences in peak ankle joint angles and excursions observed between male and female professional ballet dancers may be attributed to early engagement in jump and balance training.

The initial LDA and the post-hoc LDA revealed new insights into how foot positions might be categorised based on ankle mechanics and vGRF. A 60% improvement in model accuracy was observed following the grouping of foot positions (ungrouped: 57%; grouped: 91%); demonstrating the similarities between first and second positions, the back foot in fourth and fifth position, and the front foot in fourth and fifth position. To that end, grouping these foot positions when considering ankle mechanics and vGRF is warranted and may aid in simplifying decision-making in applied environments. The results of the present study indicate that three-dimensional ankle kinetics and kinematics play a critical role in discriminating between different foot positions, particularly through the frontal and transverse planes. It is perhaps unsurprising that frontal and transverse plane kinematics were able to discriminate the grouped front and back foot positions in fourth and fifth from other positions due to the offset and asymmetrical nature of these positions when compared to parallel, first, and second. Presently there is limited literature investigating different foot positions, making comparison challenging. Imura and Iino[80] investigated parallel and first during take-off and observed no differences in peak ankle dorsiflexion angle, ankle plantarflexion moment, or ankle plantarflexion work between parallel and first. Conversely, when Ravn et al.[109] investigated parallel and first during take-off, they observed peak sagittal plane ankle joint moments and powers in first position at least twice that of parallel. Ravn et al.[109] however, performed no statistical analysis and only three participants were included, potentially leading to inflated results.[345] Both of the aforementioned studies used different methods to calculate kinetic outcome variables, limiting any direct comparisons with our analysis. Further research is needed to better understand the demands different foot positions place on the tissues of the lower extremities during landing. Additionally, examining repeated jumping, travelling jumps, and unilateral jumps in different foot positions would also reveal further insights into the biomechanical demands of ballet jumps.

7.5.1 Practical Applications

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

7.5.2 Strengths, Limitations, and Future Directions

This research is one of few studies investigating jumping actions in both male ballet dancers and professional ballet dancers,[335] demographics which have previously been under-studied in the ballet literature. Considering male ballet dancers and professional ballet dancers will typically be exposed to greater jumping demands than female dancers and non-professionals, respectively, it is important to understand these demographics in more detail.[3] Bilateral asymmetries or limb dominance may have affected the results of this study, as only the right limb was measured during bilateral jumps. Previous work, however, has found no association between a dancer's perception of limb dominance and their kinetics during jumping.[258] Future work may wish to conduct a broader analysis of landing biomechanics in dancers which includes the trunk and entire lower extremity.

7.6 Conclusion

This study investigated the effect of sex and foot position on ankle mechanics and vGRF in professional ballet dancers. The results identified that foot position, but not sex, influences ankle mechanics and vGRF during jump landings. The absence of sex differences in lower extremity biomechanics is consistent with previous literature in dance, potentially suggesting the benefits of early adoption of jump and balance training. Frontal and transverse plane ankle mechanics had the largest impact when discriminating between different foot positions, with jump landings in fourth and fifth demonstrating greater ranges of motion, moments, and power when compared to other foot positions. Adaptations in multiplanar force and rates of force development are warranted in professional ballet dancers. Finally, following injury, full ankle range of motion should be restored prior to returning to fourth and fifth positions.

CHAPTER 8

Strength, Range of Motion, and Dynamic Joint Alignment are Poorly Associated with Ankle Mechanics and Ground Reaction Forces During Jump Landings in Professional Ballet Dancers

8.1 Abstract

Objective To investigate the associations between peak plantarflexion ankle joint moments and vGRF during jump landings, and static ankle dorsiflexion range of motion, three-dimensional ankle excursions, and lower extremity strength in professional ballet dancers.

Methods Twenty-seven professional ballet dancers volunteered to participate in this research (men = 14, women = 13). Participants attended one data collection session to measure static ankle dorsiflexion ROM and unilateral isometric lower extremity strength. Two further sessions were used to establish ankle mechanics and vGRFs during countermovement jump landings in seven foot positions, via a seven-camera motion capture system and piezoelectric force platform. Two linear mixed-effects models were used to investigate associations between the target variables and strength, static ankle dorsiflexion ROM, and three-dimensional ankle excursions. Dancer identification, sex, and foot position were entered as random effects.

Results Model fit, when considered independent of random effects, was generally poor with the predictor variables explaining little of the variance of peak plantarflexion ankle joint moments ($R^2 = 0.02$) or vGRF ($R^2 = 0.01$). Model fit improved, particularly for peak plantarflexion ankle joint moments, when random effects were considered ($R^2 = 0.65$ & 0.34). Frontal plane ankle excursion was the only predictor variable with a significant negative association with peak plantarflexion ankle joint moments ($p = .016$), although coefficient estimates were small.

Conclusion Strength, static ankle dorsiflexion ROM, and three-dimensional ankle excursions are poor predictors of load experienced at a joint and system level in professional ballet dancers. Differences between individuals, sex, and foot position may be better indicators of the load experienced during jump landings.

8.2 Introduction

The athletic demands of professional ballet are increasingly being investigated to better inform training prescription in the context of performance and injury.[160] To that end, class, rehearsal, and performance in professional ballet are characterised by a high volume of *pliés*, leg raises, jumps, and partner lifts.[3] Jumping is one area that has received attention,[335] due to the associated injury risk.[4,314] Indeed, jumping was recorded as the inciting event in 38% and 27% of time-loss injuries in professional male and female ballet dancers, respectively.[314] The distal lower extremity—collectively the foot, ankle, and shank—incur the greatest burden of injury.[314] Specifically, traumatic lateral ankle sprains and overuse bony stress fractures and stress responses are the most common jump-related injuries.[314] Subsequently, more emphasis is being placed on the biomechanics of jumping in ballet with a particular focus on the distal lower extremities.[10,335]

It is well documented from laboratory case reports that the global biomechanics of a lateral ankle sprain is typically associated with excessive plantarflexion and inversion when moving or landing from a jump.[119–122] It can be more challenging, however, to identify the contributing factors to an injury with an insidious onset, such as bony stress fractures or stress responses. The interaction between load exposure, tissue damage, and tissue adaptation is complex and challenging to measure.[56,87,346,347] Edwards,[87] suggested that cyclic loading of biological tissue—such as a high frequency of jumping on cortical bone properties—can result in tissue failure consistent with a mechanical fatigue process. Further, an increase in the magnitude of load that biological tissue is exposed to is not proportionally linear to the damage that the tissue experiences, such that higher loads cause disproportionally more damage compared to lower loads.[87,347] Thus, understanding the moderators of load magnitude during jumping and landing may reveal specific physical qualities that are associated with lower tissue damage during jumping which might be screened to facilitate targeted conditioning programs.

Lower extremity strength may be clinically meaningful when interpreting lower extremity joint mechanics during landing, as greater strength affords more movement opportunities such that a dancer (or athlete) is able to modulate the degree of joint stiffness upon landing.[89] The ability to modulate joint stiffness upon landing can directly influence the load experienced by the lower extremity, where stiff landings results in higher peak forces and compliant landings result in lower peak forces.[348,349] Lower extremity strength is only one potential moderator when considering a dancer's biomechanics on landing. Howe et al,[96] for example, demonstrated that both strength and mobility—specifically ankle dorsiflexion ROM—should be considered when assessing how landing strategies might moderate peak forces. Ankle dorsiflexion ROM can directly influence the movement affordances available to the ankle and knee throughout the landing phase of a jump, facilitating more compliant landings, and potentially reducing peak forces.[95]

Understanding the moderators that may affect the load experienced by the distal lower extremities when jumping and landing can better inform the physical screening and prescription of training in a performance and rehabilitation context.[69,83,87] This study aimed to investigate the associations between peak ankle joint moments and vGRF during jump landings and static ankle dorsiflexion ROM, three-dimensional ankle excursions, and unilateral isometric lower extremity strength in professional ballet dancers.

8.3 Methods

8.3.1 Study Design

A cross-sectional study design was employed to investigate the determinants of peak plantarflexion ankle joint moments and vGRF during jump landings in professional ballet dancers. Participants attended three data collection sessions in a randomised order, separated by 13.5 ± 20.6 days. One session was used to establish maximum strength and range of motion of the lower extremity. Maximum strength was established using unilateral variations of maximal isometric force tests across the squat, standing plantarflexion, and seated plantarflexion positions.[184] Static ankle dorsiflexion ROM was established during a weight-bearing lunge test.[130] Two sessions were used to establish ankle mechanics and vGRF variables during countermovement jumps in seven different foot positions (Figure 8.1). All testing was conducted in the Royal Opera House, UK.

8.3.2 Participants

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

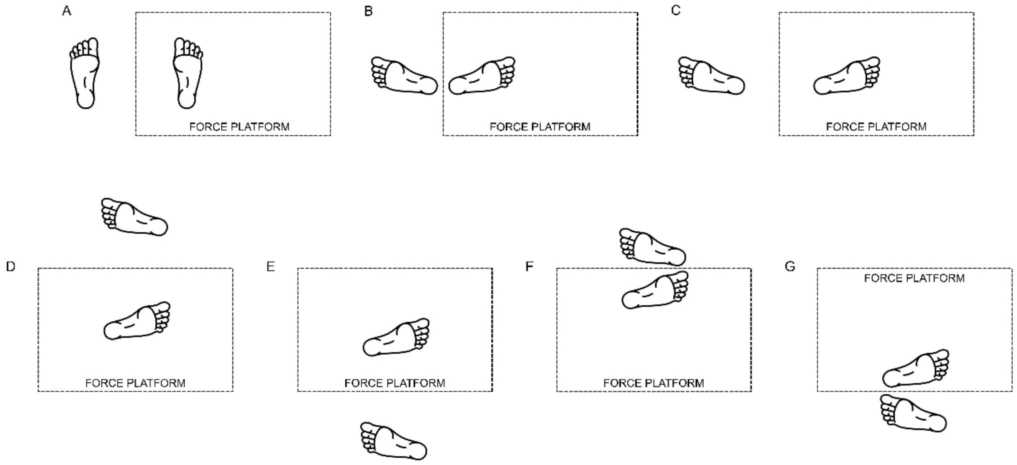


Figure 8.1 The foot positions tested in the present study with reference to the force platform. (A) parallel, (B) first, (C) second, (D) fourth back, (E) fourth front, (F) fifth back, (G) fifth front. Grouped first and second position indicates that all jumps depicted in (B) and (C) were grouped; Grouped front foot position indicates that all jumps depicted in (E) and (G) were grouped; Grouped back foot position indicates that all jumps depicted in (D) and (F) were grouped.

8.3.3 Procedure

8.3.3.1 Isometric Force and Weight-Bearing Lunge Testing

Following a progressive and standardised warm-up participants performed three five-second maximal isometric contractions on the right limb during a unilateral squat, unilateral standing plantarflexion, and unilateral seated plantarflexion test.[184] A twenty-second inter-repetition and a two-minute inter-set recovery were provided.

The vGRF data were collected using a force platform incorporating 4 strain gauge load cells (MUSCLELAB, Ergotest Innovation AS, Stathelle, Norway) sampling at 1000 Hz. An isometric rig, with 2.5 cm adjustable vertical spacing, and a barbell (Sportesse, Somerset, United Kingdom) were used for all tests, with a 3.3 cm thick foam pad (Power Guidance, London, England) around the barbell for comfort. Bodyweight was calculated from a five-second static trial where participants were standing motionless on the force platform. Participants were required to wear their own shoes during testing. Participants were instructed to "push maximally into the barbell" before each trial. Each trial was initiated by the researcher instructing the participant to adopt the relevant position and then counting down "3, 2, 1, Push". The force platform was zeroed prior to each set. A detailed outline of each of the isometric force tests conducted is described elsewhere.[184]

Three weight-bearing lunge tests were completed with each participant. The maximum shin angle during each weight-bearing lunge test was recorded using an inclinometer (Acumar Digital Inclinometer, Lafayette Instrument Company, Indiana, USA). A detailed overview of the testing procedure is described elsewhere.[130]

8.3.3.2 Jump Testing

Participants completed a standardised and progressive warm-up prior to testing. Retroreflective markers (22 mm diameter) were attached to the right: greater trochanter, medial and lateral joint lines of the knee, medial and lateral malleolus, posterior aspect of the calcaneus, superior aspect of the navicular, medial aspect of the 1st metatarsal head, and the lateral aspect of the 5th metatarsal head using double-sided adhesive tape and adhesive spray. A curved rigid moulded cluster with four retroreflective markers was attached to the lateral aspect of the right shank using cohesive elastic tape and electrical tape (Figure 8.2).

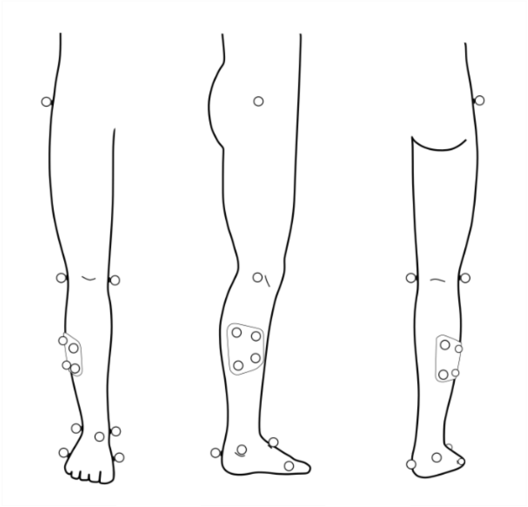


Figure 8.2 Marker placement on the right limb from the anterior, lateral, and posterior aspects.

Participants completed five maximal bilateral countermovement jumps across seven different foot positions during one data collection session. These positions included parallel, first, second, fourth with the front foot on the force platform, fourth with the back foot on the force platform, fifth with the front foot on the force platform, and fifth with the back foot on the force platform (Figure 8.1). Foot positions were grouped based on their biomechanical profile during jump landings (parallel, grouped first and second position, grouped front foot, and grouped back foot). Participants also completed five maximal bilateral countermovement jumps across parallel and first positions during a separate data collection session. The reliability of ankle mechanics and vGRF measures during jump landings in professional ballet dancers are presented elsewhere.[350]

Prior to jumping, the right limb was positioned on the force platform and the left limb was positioned on a wooden frame that surrounded the force platform (Figure 8.1). The participant's hands were placed on their shoulders for all jumps. Order effects were mitigated by alternating jumps until one jump in each foot position was performed within a set. Twenty seconds of inter-rep rest and two minutes of inter-set rest were provided.[319]

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

8.3.4 Data Analysis

8.3.4.1 Isometric Force and Weight-Bearing Lunge Testing

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

8.3.4.2 Jump Testing

Marker trajectories were reconstructed and labelled in Vicon Nexus (Vicon Motion Systems Ltd, Oxford, United Kingdom) before being processed in Visual 3D (v2021.113 C-Motion©, USA). All marker trajectory gaps consisted of seven frames or fewer and were interpolated using cubic splines. A foot and a shank segment were created in Visual 3D. The foot was defined by the medial and lateral malleolus as the proximal endpoints and the medial aspect of the 1st metatarsal head and the lateral aspect of the 5th metatarsal head as the distal endpoints. The shank was defined by the medial and lateral joint lines of the knee as the proximal endpoints and the medial and lateral malleolus as the distal endpoints. Foot and shank segment inertia parameters were defined in line with de Leva.[321] Individual and cluster markers for the foot and shank were used to track segments during dynamic trials. Marker and ground reaction force data were filtered at 8 Hz using a low-pass fourth-order Butterworth filter, determined via residual analysis.[322] An inverse kinematics approach was used to estimate the pose of the segments,[320] allowing three degrees of rotation but no translation between the foot and shank segments. Ankle joint angles were calculated using an XYZ Cardan rotation sequence. Kinematic data and segmental inertial data were combined with ground reaction force data to calculate plantarflexion ankle joint moment using inverse dynamics with the shank segment used as both the reference segment and the resolution coordinate system.[321] Ankle joint moment was normalised for comparisons between participants[323]—leg length was replaced with height:[324]

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

Vertical ground reaction force data were reprocessed and filtered at 250 Hz using a low pass fourth-order Butterworth filter, determined via residual analysis,[322] to calculate normalised vGRF:

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

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

The landing phase of each jump was extracted; the start of the trial was identified by the point of initial contact following a period of flight where vGRF was > 50 N and the end of the trial was identified by the point at which data collection ceased. Peak values of ankle mechanics and vGRF measures were then calculated through all planes of motion. Peak ankle joint moment and peak landing vGRF were normalised to jump height.[351] Three-dimensional ankle excursions were calculated by subtracting the minimum ankle angle from the peak ankle angle across each plane of motion.

8.3.5 Statistical Analysis

Two linear mixed-effects models were constructed using the R package *lme4*.[195] The first model was to establish associations between peak plantarflexion ankle joint moment and dancer strength (squat, standing plantarflexion, and seated plantarflexion isometric force tests), static ankle dorsiflexion ROM (weight-bearing lunge test), and three-dimensional ankle excursions. The second model was to establish associations between peak vGRF and the aforementioned predictor variables. For both models, strength, static ankle dorsiflexion ROM, and three-dimensional ankle excursions were entered as fixed effects and the dancer's unique identification, sex, and grouped foot position were entered as random effects. All numeric data were scaled using the R *base* package before models were computed.[300] An alpha level of $p < .025$ was set to account for the multiplicity of two outcome variables. Model goodness-of-fit was assessed via a marginal (fixed effects only) and conditional (both fixed and random effects) R^2 value using the R package *MuMIn*.[352] Normality, linearity, homoscedasticity, and independence of residuals were confirmed for both models. The second model demonstrated a non-normal distribution of residuals, however, linear mixed-effects models are robust to violations of normality, and thus no transformation was applied.[353] All data processing and statistical analysis were conducted using R (version 4.2.1, R Foundation for Statistical Computing, Vienna, Austria).

Table 8.1 Mean ± SD for static dorsiflexion range of motion and unilateral isometric force tests.

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

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

8.4 Results

Descriptive statistics for static ankle dorsiflexion ROM and unilateral isometric lower extremity strength are presented in Table 8.1. Six jumps were corrupt and unable to be processed and a further six jumps were identified as extreme outliers and subsequently removed (n = 12; 0.8%), as such a total of 1338 jumps were included in the analysis.

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

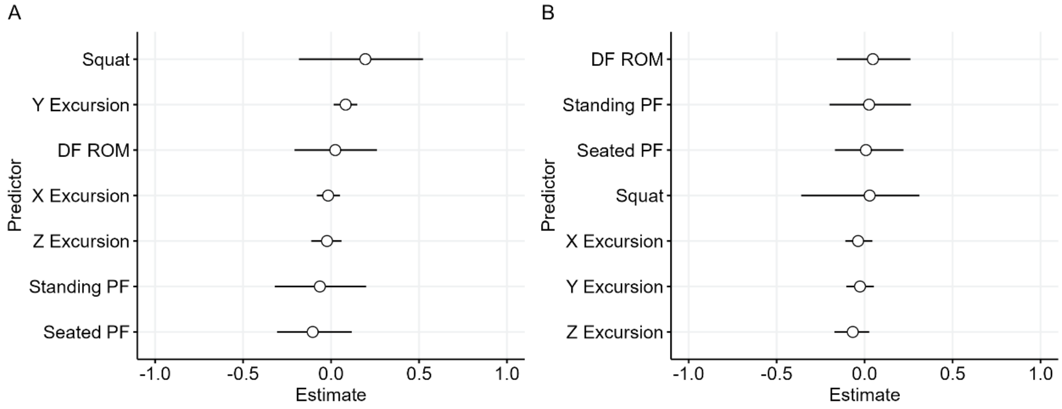


Figure 8.3 Coefficient estimates and 95% confidence intervals for the linear mixed-effects models investigating (A) peak normalised plantarflexion ankle joint moment and (B) peak normalised vGRF. A positive coefficient estimate indicates that an increase in the predictor value is associated with an increase in the target variable whereas a negative value indicates the opposite. Data are scaled (-1.0–1.0) and not true to their original units to facilitate comparison on a single axis. DF, dorsiflexion; ROM, range of motion; PF, plantarflexion

The linear mixed effects model investigating factors associated with peak vGRF revealed no significant main effects of any variable (*p* = .170–.942). The marginal R^2 value indicated that 1.0% of the variance in peak vGRF was explained by dancer strength, static ROM, and ankle excursions. Conversely, the conditional R^2 value indicated that 34.3% of the variance in peak vGRF was explained by dancer strength, static ROM, ankle excursions, dancer’s unique identification, sex, and foot position. The coefficient estimates for both models are presented in Figure 8.3. The raw data for both models are presented in Figures 8.4 and 8.5. The raw data illustrating random factors are presented in Figures 8.6 and 8.7.

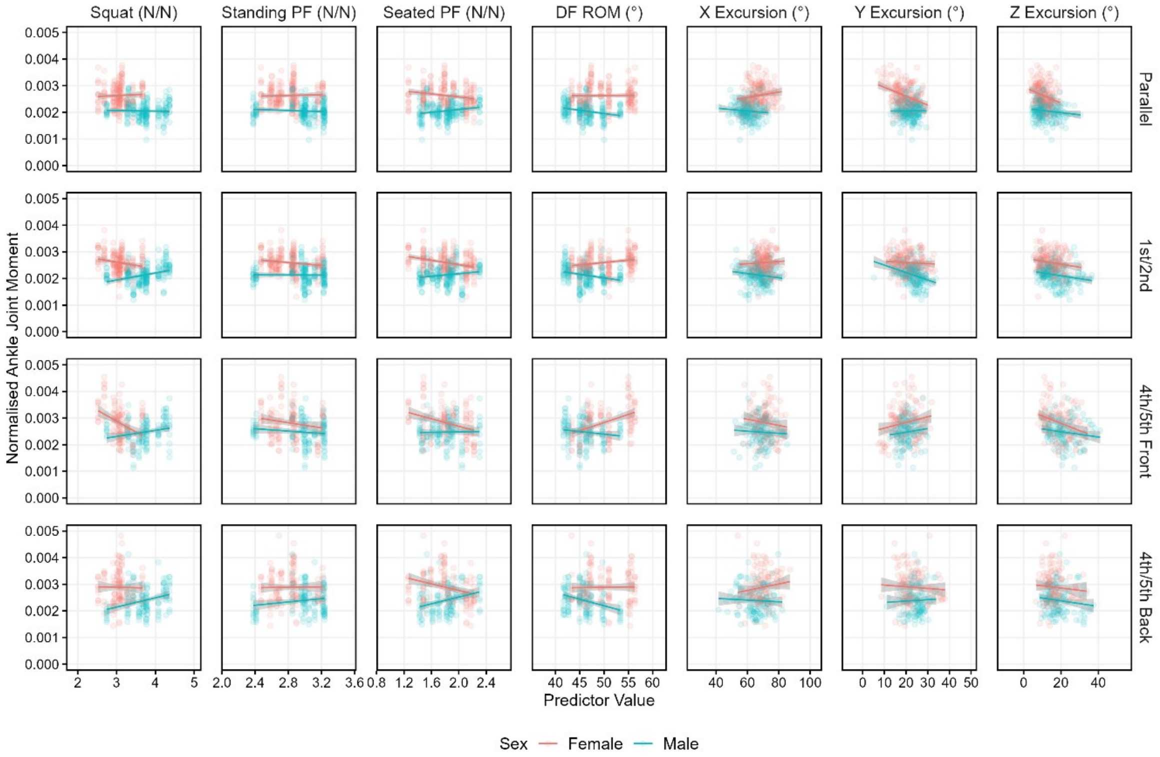


Figure 8.4 Raw data illustrating the associations between peak normalised plantarflexion ankle joint moment and fixed factors (dancer strength, static ROM, and ankle excursions) accounting for random factors (sex, grouped foot position, and dancers' unique identification). DF, dorsiflexion; ROM, range of motion; PF, plantarflexion.

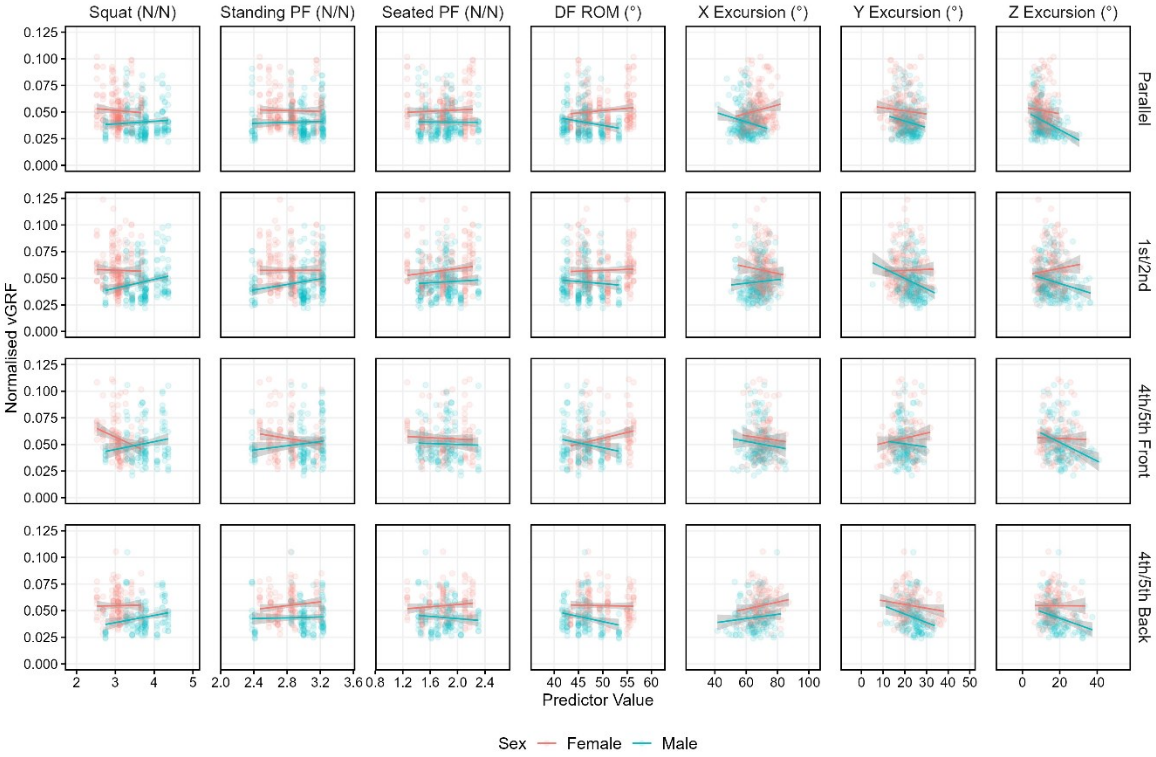


Figure 8.5 Raw data illustrating the associations between peak normalised vGRF and fixed factors (dancer strength, static ROM, and ankle excursions) accounting for random factors (sex, grouped foot position, and dancers' unique identification). DF, dorsiflexion; ROM, range of motion; PF, plantarflexion.

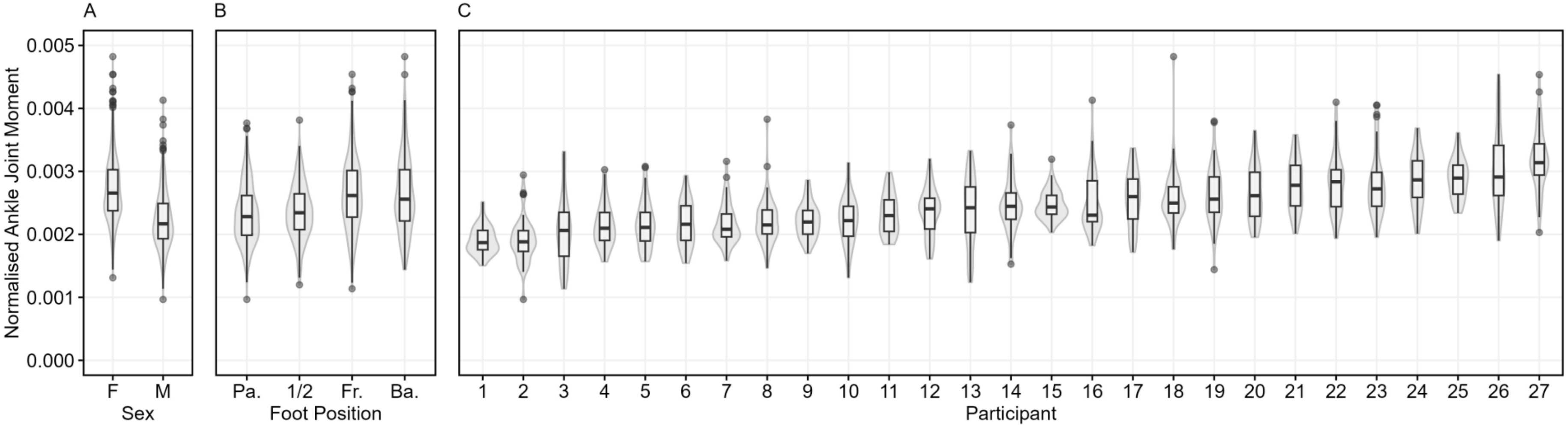


Figure 8.6 Raw data illustrating the associations between peak normalised plantarflexion ankle joint moment and random factors (sex, grouped foot position, dancers' unique identification). Pa., Parallel; 1/2, first and second; Fr., front foot in fourth and fifth; Ba., back foot in fourth and fifth position.

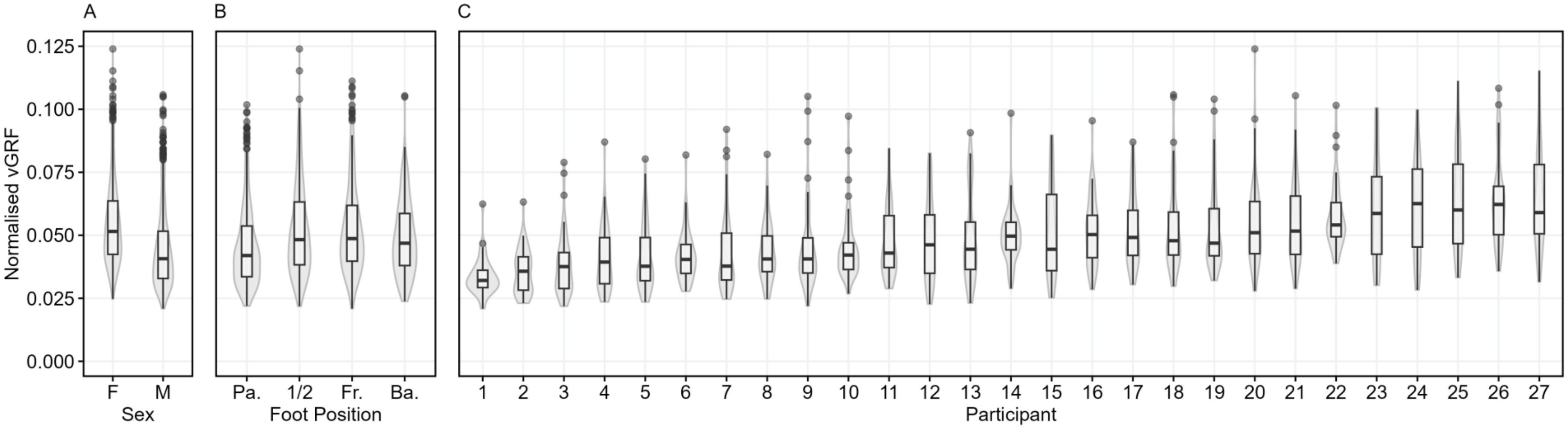


Figure 8.7 Raw data illustrating the associations between peak normalised vGRF and random factors (sex, grouped foot position, dancers' unique identification). Pa., Parallel; 1/2, first and second; Fr., front foot in fourth and fifth; Ba., back foot in fourth and fifth position.

8.5 Discussion

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

No significant associations were identified between unilateral isometric lower extremity strength and either of the target variables. Several studies have identified that lower extremity strength characteristics are associated with desirable lower extremity biomechanics—such as dynamic joint alignment, smaller vGRFs, and reduced joint stiffness or moments—during jump landings.[75,89–93] Conversely, others have identified no association between lower extremity strength characteristics and lower limb biomechanics during landing tasks,[354–356] one of which has even called for a paradigm shift in the design of injury prevention programs as a consequence.[355] The measurement of strength across all studies—including those that have and have not found associations with landing biomechanics—has been inconsistent, measuring isometric,[75,89,90,92,93,354–356] isotonic,[356] and isokinetic[91] strength across the ankle,[356] knee,[89,91,92,355,356] hip,[75,90,93,354–356] and trunk[356] using BW endurance exercise,[356] HHD,[75,90,354–356] and isokinetic dynamometry.[89,91–93,356] All of the previous studies have measured strength isolated to a single joint, as opposed to the present study which has measured strength using multi-joint positions. It is possible, therefore, that isometric force testing may not be as sensitive as isolated joint strength testing when assessing the association of strength and joint-specific mechanics.

Much of the research that has found associations has focused on the strength characteristics and landing biomechanics of the knee and hip as opposed to the ankle.[75,89–93] Further, several of these studies have selected lower limb kinematics—as opposed to kinetics—as their target variables due to the association between dynamic joint alignment and anterior cruciate ligament injury.[75,92,93,354,355] It is plausible that kinematic associations are present in the absence of kinetic associations in the aforementioned studies. To the authors' knowledge, no previous literature has investigated lower extremity strength and ankle joint moments. Greater ankle plantarflexion strength likely makes a desirable contribution to tissue capacity and dynamic joint stiffness around the ankle; however, it does not appear to predict landing biomechanics.

No associations between static dorsiflexion ROM and the target variables were observed. Mixed findings have been reported in studies in which ankle dorsiflexion has been investigated. Some authors have shown associations between dorsiflexion ROM and landing kinetics[94] or kinematics,[94,95] whereas others have not.[95,357,358] Further, some authors have demonstrated joint-level associations (e.g., ankle or knee moments) but not system-level associations (e.g., vGRF)[129] with ankle dorsiflexion ROM. Such conflicting findings have previously been attributed to differences in movement strategies, where compensations in frontal and transverse planes of motion have facilitated more compliant landings in individuals with reduced dorsiflexion range of motion.[359] The reference data we provide, however, suggest that all professional ballet dancers had high degrees of ankle dorsiflexion when compared to the participants in similar research,[94,129,358] although differences in assessment methods were noted in two of the three studies. We speculate that there may be an interaction effect between strength and static ankle dorsiflexion ROM that modulates joint stiffness and dynamic joint alignment.

We observed associations between frontal plane ankle excursion and peak plantarflexion ankle joint moments, such that smaller frontal plane ankle excursions may be indicative of larger plantarflexion joint moments. In line with previous authors, frontal (or transverse) plane excursions may manifest where additional ankle ROM is desired or a lack of dynamic joint alignment is present.[359] It should be noted, however, that the model fit was poor and the coefficient estimates, indicative of effect size, were small. To that end, practitioners working within dance should interpret these findings with caution.

The fixed effects selected in the present study resulted in a poor fit across both models when considered independent of the random effects. When the random effects were accounted for, however, both models' fit improved, although peak vGRF was to a lesser degree. As such, dancer strength, static ankle dorsiflexion ROM, and three-dimensional ankle excursions are poor predictors of the load experienced by the ankle and system during jump landings in professional ballet dancers. Dancer sex, jump position, and individual variation are more suitable variables to consider when assessing whether a dancer will be exposed to greater or lesser magnitudes of load during jump landings. It should be noted that the lack of association between strength and ROM and the target variables does not indicate that these physical qualities are not important to increase injury resilience.[209,359–361] Future work may wish to prospectively investigate whether these variables (strength, static ROM, and ankle excursions) increase dancer resilience to injury (i.e., by increasing tissue capacity) as opposed to using them to predict the peak load experienced at a joint and a system level.

8.5.1 Strengths And Limitations

Previous work is sparse pertaining to male and professional ballet dancers,[335] and, thus, the present study offers new insights for practitioners working within dance medicine and science. A limitation, however, is that only the right limb was measured during bilateral jumps; investigating the entire kinetic chain across both limbs may yield different results. Larger laboratories with additional cameras may facilitate more detailed analyses. To that end, there are logistical challenges associated with applied research within a professional ballet company due to dense rehearsal schedules which limit time and space.[5] Future work may benefit from permanent laboratories that are established within the residence of professional companies. The present study included maximum isometric strength as a predictor variable, other muscle contractions (such as isotonic or isokinetic) or forms of strength (such as RFD) may yield different results.

8.5.2 Practical Applications

The model goodness-of-fit, when considered independent of random effects, was generally poor. As such, practitioners working with professional ballet dancers should be aware that unilateral isometric lower extremity strength, static ankle dorsiflexion ROM, and three-dimensional ankle excursions will not indicate the magnitudes of load experienced at the ankle joint or a system level during jump landings. Nevertheless, unilateral isometric lower extremity strength, static ankle dorsiflexion ROM and three-dimensional ankle excursions are likely important factors to consider in the context of injury.[209,359–361] Dancer sex, the foot position in which they land, and the individual variation between dancers are more appropriate factors to consider when assessing the load experienced at a joint or system level. To that end, regular physical profiling, appropriate load management, and individualised training programs are likely important to minimise injury risk. This study also provides reference data relating to unilateral isometric lower extremity strength and static dorsiflexion ROM in professional ballet dancers.

8.6 Conclusion

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

CHAPTER 9

General Discussion

9.1 Context

A growing body of work has investigated jumping and landing in ballet dancers due to the suspected performance requirements and associated injury burden. Presently, there is limited evidence to support the association between jumping and landing activities and injury in professional ballet dancers. Further, the moderators of load on the lower extremity during jumping and landing are not well understood. Thus, the aims of this thesis were to:

1. Describe the burden of injury in ballet and review what is currently known regarding jumping and landing biomechanics in ballet dancers
2. Develop reliable ways to assess the strength and landing mechanics of ballet dancers
3. Investigate the determinants of landing in professional ballet dancers

This discussion will focus on each aim and address the key findings, practical applications, limitations, and potential areas for future research.

9.2 Understanding the Problem

Section 1 addressed the first aim of this thesis and was split into two distinct chapters (Chapters 3 and 4). Chapter 3 intended to build on the previous epidemiology work in professional ballet,[4,46,84–86] which to date has not been presented in a format consistent with elite sport.[7,8] To that end, Chapter 3 did not solely focus on injury epidemiology associated with jumping and landing and instead provided a comprehensive overview of injury epidemiology in professional ballet. Subsequently, the injury epidemiology associated with jumping and landing activities is framed within the wider context of injury in professional ballet. In line with previous research,[4] it was apparent that jumping and landing activities were the most common mechanism of injury, especially for ankle sprains and stress fractures/responses to the distal lower limb. More recently, multi-centre work has provided further confirmation that jumping and landing activities are the most common mechanisms of injury around the foot and ankle in professional ballet dancers.[362] Jumping and landing as the primary mechanism of injury to the distal lower extremities is perhaps the most significant take-away within the context of this thesis, as it provides a clear rationale for further investigation into the biomechanics of such activities in this population.[83]

Chapter 4 systematically synthesised the literature investigating the biomechanics of jumping and landing activities in ballet dancers. Much of the literature has focused on landing kinetics and the primary outcome measure of these investigations was often vGRF, providing limited insights into the kinetic profile of the foot and ankle during landing. A more comprehensive investigation of kinetics and kinematics at both a joint and system level was considered important given that i) the two most burdensome injuries identified in Chapter 3 are associated with landing as opposed to taking off;[121,363] and ii) the technical constraints of ballet, such as an erect posture with minimal hip and trunk flexion during countermovements, result in a proximal-to-distal shift in joint contributions.[80,109] Further, applying such investigations to understanding the five codified foot positions that characterise classical ballet may provide insights that can be contrasted against one another and generalised to more complex movements. It was also noted that most of the included studies exclusively investigated non-professional (18/29) and female (19/29) ballet dancers, and several did not specify the sex of participants (6/29). Sex differences in dancers have been reported previously but only in mixed genres.[117,124,240] The limited number of studies investigating male and professional dancers is a notable gap within this area of research as professional ballet dancers are likely to jump more than non-professional dancers due to the dense rehearsal schedules associated with a professional company.[6] Moreover, Chapter 3 indicated that jumping and landing was the typical mechanism of injury of men who had sustained stress fractures/responses to the distal lower extremity.

9.3 General Methods

Section 2 addressed the second aim of this thesis and was split into two distinct chapters (Chapters 5 and 6). Chapter 5 investigated the within- and between-session reliability of vGRF during lower limb isometric force tests. The importance of Chapter

5 was grounded in the idea that a measure of strength would be used later in the thesis to establish the association of landing mechanics and lower limb strength. To the author's knowledge, this is one of the few studies to investigate both unilateral and bilateral variations of isometric force tests in the same population,[364] yielding interesting and unanticipated findings. For example, it was apparent that force production in the standing tests—which required direct axial loading due to the placement of the bar on the upper back—was similar across both unilateral and bilateral variations. It is speculated that axial loading during bilateral tests is the limiting factor to achieve higher forces. Thus, unilateral tests may provide a more accurate representation of lower limb force production as opposed to tolerance to axial load. As such, it was decided that unilateral variations would be included later in the thesis instead of, or, in addition to, bilateral variations. The primary finding of Chapter 5 was that vGRF across all variations of isometric force tests was reliable, in line with previous research in this area.[182,183] It should be noted, however, that no measure of validity across positions was calculated. We speculate that across all three positions, an accurate representation of lower limb strength can be assumed as validations of similar tests exist in the literature.[301,365] As such, it was decided that all measures of unilateral isometric strength were to be included in any further analysis to mitigate the risk that one independent measure may not provide a true representation of lower limb strength.

The purpose of Chapter 6 was to establish the reliability of ankle mechanics and vGRFs during jump landings in turned-out and parallel foot positions in professional ballet dancers. The rationale for Chapter 6 was twofold; firstly, to understand whether jumping in a more dance-specific way would negatively influence reliability, and, secondly, which variables were more or less reliable during these jumps. Chapter 4 identified that no previous work in this space has been conducted. The biomechanical analysis of jump landings focused on the distal lower extremity because the associated burden of injury of the foot, ankle, and lower leg was identified in Chapter 3. Reliability ranged from *poor* to *excellent* across both foot positions and all included variables. Between-session reliability was greater than within-session reliability suggesting that individual trials are highly variable and a mean of several trials may provide a more stable outcome measure to use for further analyses.[331,332] Peak ankle velocity demonstrated the lowest reliability, particularly through the frontal and transverse planes. Conversely, jump height, peak ankle angles, and multiplanar ankle excursions demonstrated the greatest reliability. All sagittal plane variables were deemed to be reliable, however, most frontal and transverse plane variables also provided *moderate* to *good* reliability (excluding ankle velocity). Subsequently, the interpretation of ankle velocity in future analyses should be viewed with caution as it may be a less stable outcome measure. The primary finding, however, was that jump landings in a turned-out position were not less reliable than in a parallel position, providing confidence for the subsequent chapters investigating various ballet foot positions.

9.4 Jumping and Landing in Ballet

Section 3 addressed the third aim of this thesis and was split into two distinct chapters (Chapters 7 and 8). Chapter 7 aimed to understand the impact of sex and foot position on jump landings in professional ballet dancers. It was identified in Chapter 4 that two studies have investigated jumps in a turned-out and parallel foot position in professional ballet dancers.[80,109] Given that classical ballet is characterised by five codified foot positions, it is a logical progression to investigate all foot positions in more detail. To that end, the association between sex and foot position on ankle mechanics and vGRFs during jump landings was determined. No multivariate main effects of sex were identified, although potential univariate effects may be present (e.g., sex differences in jump height). The lack of sex differences observed may be explained, in part, by the normalisation of all kinetic metrics, removing the influence of factors such as body mass or height. Previous work has observed greater lower extremity joint angles in women compared to men in sporting populations during landing tasks.[123,343] The findings of Chapter 7 support previous hypotheses that integrating jump and balance training from a young age, often associated with dance training, may reduce the disparity in landing mechanics between men and women.[117,123] Conversely, main effects of foot position were identified. Kinematic differences were clearly defined between the asymmetrical positions of fourth and fifth and the symmetrical positions of parallel, first, and second, with greater frontal plane peak angles and excursions observed during landings in fourth and fifth positions. The kinematic differences observed indicate that when a return-to-dance pathway is being planned, full ankle ROM should be restored prior to returning to fourth and fifth positions. That being said, the integration of ballet—and the demands it places on the ankle—can be progressive and applied creatively through a multidisciplinary approach by collaboration between the artistic and medical staff. Greater frontal and transverse plane kinetic demands were also observed during landing in asymmetrical positions, indicating a need for multidirectional force and rates of force development in professional ballet dancers.

The aim of Chapter 8 was to draw all the aspects of this thesis together to understand whether it was possible to predict the load experienced at a joint or system level based on the static ROM, strength, and dynamic alignment during jump landings in professional ballet dancers. The rationale for this chapter was as follows: if load could be predicted, such that stronger, more flexible dancers with better landing mechanics experienced lower loads, then there would be clear outcomes to go forward when aiming to reduce jump-related injuries in this population. To that end, two linear mixed-effects models were conducted to investigate the association of ankle joint moments and vGRF with dorsiflexion ROM, isometric strength, and ankle excursions (fixed effects), accounting for foot position, sex, and unique dancer identification (random effects). Alas, the load experienced at a joint and system level is highly complex and many factors will interact to determine the movement strategy adopted,[69] even in a laboratory setting. It was apparent that the predictor variables were poorly associated with the outcome variables, explaining little of the variance (R^2 = 1–2%). When the random effects were considered, however, the goodness-of-fit of each model improved, suggesting that foot position, sex, and unique dancer identification may have a greater influence on the load experienced at the ankle and system level. Although measures of ROM, strength, and dynamic alignment were unable to predict the load experienced at a joint and system level, it is believed that such measures will impact the load tolerance of local structures.[209,359–361] It should be noted, however, that greater strength may be a double-edged sword; where it may serve as a protective mechanism through improved stress-strain properties around the local tissues,[157] it may also result in higher magnitudes of force being expressed to those tissues as a dancer (or athlete) jumps higher, turns more quickly, or travels further. As discussed earlier in the thesis, higher magnitudes of load result in disproportionately more damage to local tissues compared to lower loads.[87] Thus, the ROM available to joints and the movement strategies utilised during dynamic tasks—alongside appropriate load management—are likely key to managing jump-related injuries. Future work may wish to prospectively investigate the relationship between physical profiles, landing mechanics, training load, and injury.

9.5 Practical Applications

This thesis provides numerous opportunities to integrate findings into applied practice. Within Section 1, Chapter 3 provides a framework in which injury epidemiology can be reported within dance. Further, practitioners working within these environments can utilise the information reported to proactively implement interventions to address the most burdensome injuries, such as ankle sprains, ankle impingement, and bone stress fractures/responses. Within Section 2, Chapters 5 and 6 both provide reliable methods to assess strength and landing mechanics, reference values for comparison, and MDC values to interpret improvement or a lack thereof. Appendix D and E demonstrate examples of how the findings from this thesis may be integrated into applied environments where the innovation of new equipment can manifest and reference values/MDC values can be built into athlete data management software. Within Section 3, the findings from Chapter 7 indicate that the grouped foot positions could accurately discriminate different biomechanical profiles across all of the included target variables. The interpretation of this is that the foot positions within each of the grouping categories can be considered similar from a biomechanical perspective which may facilitate graded and criteria-led rehabilitation within applied environments. Lastly, Chapter 8 provides a stark reminder to applied practitioners that strong and flexible athletes are not necessarily exposed to lower joint and system-level loads, and an individualised approach to physical and technical development—where possible—should be embodied.

9.6 Limitations and Future Directions

There is a clear need for an updated and genre-specific consensus statement outlining best practice guidelines on how to record and report injury epidemiology data in professional ballet, similar to that seen in sport. This, in time, may result in a positive cascade of other genre-specific consensus statements across dance forms that are currently poorly understood and underfunded. The three most burdensome injuries identified provide clear direction for future investigations that may reveal further insights into injury risk factors, prognoses, and rehabilitation strategies that can be leveraged within applied practice.

Within professional dance, it is important to create a safe environment in which young dancers feel that can be transparent about injury without negative repercussions. An example of this may include offering contracts to talented apprentices irrespective of injury status at the end of their first year when they demonstrate the appropriate technical, physical, and psychological attributes to be a high-performing members of the company. Further, the workload of senior-ranking dancers should be prioritised and appropriately distributed across available dancers to ensure no single dancer is overloaded. It is particularly challenging to do this when multiple choreographers choose to cast the same individuals in leading roles. Integrating science and medicine practitioners at the point of artistic planning may facilitate the appropriate distribution of workload across dancers.

The present thesis has established the reliability of vGRF during unilateral isometric force tests and used these tests to investigate the associations between strength and jumping. It is important to recognise that much of the existing literature investigating isometric force testing has established the reliability of additional force-time variables, including RFD and impulse at various time points (e.g., 50, 100, 150, 200 ms).[366,367] Future work may wish to establish the reliability of such force-time variables across unilateral and ankle-biased isometric force testing. Further, it was established in Chapter 8 that where associations have been made between strength and landing mechanics, measures of isolated joint strength have been used. The sensitivity (and validity) of compound isometric force testing to accurately establish the force-producing characteristics of a specific joint may influence the magnitude of associations it is able to detect. Further investigations into the sensitivity and validity of contemporary isometric force testing are therefore warranted.

Future research is required to validate isometric plantarflexion tests (e.g., against isokinetic dynamometry).[168] Other measures of foot and ankle strength may also be of interest to practitioners working within this genre of dance. For example, it may be worth establishing robust measures of ankle inversion and eversion strength. It should also be acknowledged that only a subsection of participants in Chapter 5 were professional dancers. This was largely due to the rehearsal demands at that point of the season and the risk of 'research fatigue' on the dancers due to multiple ongoing projects within Ballet Healthcare at the time. Although not sufficiently powered, a sub-analysis was conducted on the eight professional ballet dancers which revealed *excellent* reliability and comparable MDC values across all positions and outcome measures (ICC: 0.94–0.99; CV: 1.6–7.0%; MDC: 81–202 N).

There is an opportunity to prospectively investigate the impact of physical qualities on injury risk within professional ballet. Practitioners within applied environments should continue to progress the culture of dance science and medicine, such that the feasibility of prospective research of this nature improves. Presently, many professional companies do not conduct physical profiling *en masse* frequently enough to warrant such research questions.

9.7 Conclusion

This thesis aimed to partially fulfil a sports injury framework by following a logical process of establishing injury epidemiology, identifying risk factors, establishing reliable methods of investigating potential risk factors, and investigating these risk factors in more detail.[17–19] Inspired by Bittencourt et al,[69] attempts were made to retain a level of complexity through each analysis and not fall into the trap of reductionism (Figure 9.1). That being said, complex systems are named aptly. In summary, this thesis established the injury epidemiology of professional ballet dancers, identifying jumping and landing activities as a common injury mechanism. The landscape of research investigating jumping and landing in ballet dancers was synthesised through a systematic review, highlighting potential areas for further investigation. Two chapters established reliable methods to assess i) lower extremity strength using isometric force tests; and ii) distal lower extremity ankle mechanics and GRFs during jump landings in parallel and turned-out foot positions. Chapter 7 established the influence of sex and multiple ballet-specific foot positions during jump landings for the first time in professional ballet dancers. The last chapter drew upon all aspects of this thesis in an attempt to identify the association of ROM, strength, and dynamic alignment with ankle joint moments and vGRF. The lack of association between predictor variables and target variables indicates that the load experienced at a joint and system level cannot be accurately predicted based on the physical qualities included in the analyses. Applied practitioners should be congnisent of the risk factors associated with injury in professional ballet dancers and this thesis provides suggestions on how a multidisciplinary team may approach these in a systematic way.

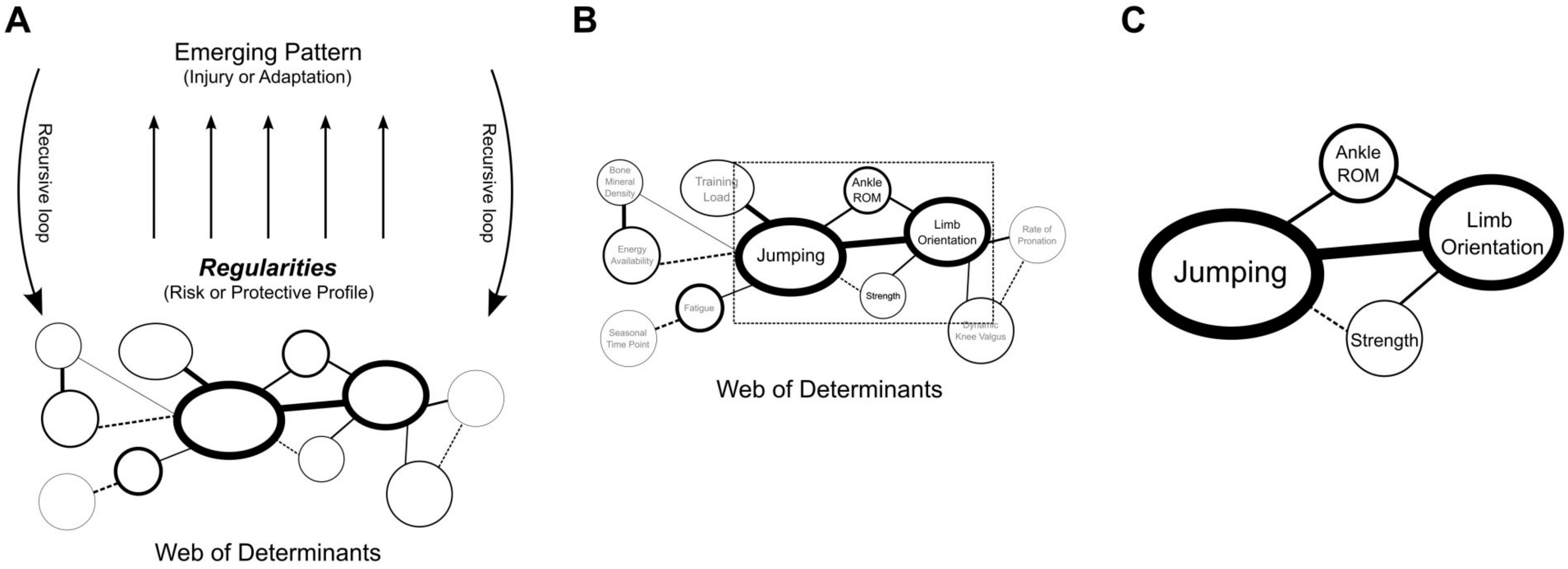


Figure 9.1 A visual interpretation of how Chapter 8 aimed to build on previous work by identifying some of the potential factors that may contribute to an injury's 'web of determinants and investigating them in more detail. It should be noted that other factors are purely anecdotal and do not represent all of the factors that may interact to result in an emerging pattern.

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Appendix A. Ballet Jump Glossary

Name	Description	Limbs involved in take-off and landing	Beats	Direction
Sauté (1st position)	A bilateral vertical jump from 1st position.	2-to-2	0	Vertical
Sauté (2nd position)	A bilateral vertical jump from 2nd position.	2-to-2	0	Vertical
Changement	A bilateral vertical jump from and to 5th position, in which the legs are switched once while in the air.	2-to-2	0	Vertical
Échappé Sauté	A bilateral vertical jump alternating between 5th and 2nd position, in which the legs are switched during each landing in 5th.	2-to-2	0	Vertical
Entrechat Six	A bilateral vertical jump from and to 5th position, in which the legs are switched three times while in the air.	2-to-2	3	Vertical
Entrechat Trois	A bilateral vertical jump from 5th position landing on a single leg, in which the legs are switched once while in the air.	2-to-1	1	Vertical
Temp Levé	A unilateral vertical jump.	1-to-1	0	Vertical
Pas Jeté	A unilateral vertical jump from one leg in 5th position landing on the other leg, in which the leading leg is extended and brushed outwards during take-off.	1-to-1	0	Horizontal
Assemblé	A unilateral lateral take-off from 5th position and bilateral landing to 5th position.	1-to-2	0	Horizontal
Grand Jeté	A unilateral jump travelling, taking-off from one leg and landing on the other, in which the legs will be split while in the air. The leading leg leaves the floor with the knee extended.	1-to-1	0	Horizontal
Saut de Chat	A unilateral jump travelling, taking-off from one leg and landing on the other, in which the legs will be split while in the air. The leading leg leaves the floor with the knee flexed and extends in the air at full flight .	1-to-1	0	Horizontal
Sissonne Fermée	A bilateral take-off from 5th position, moving forward, landing on a single leg and closing the trailing leg into 5th position	2-to-1	0	Horizontal
Entrelacé	A vertical take-off from one leg landing on the other, in which the dancer rotates 180 degrees while in the air. The leading leg is extended in front and then switched prior to landing with the trail leg extended behind.	1-to-1		Vertical
Ballonné	A vertical unilateral jump while the contralateral limb is extended out to the side.	1-to-1	0	Vertical
Grand pas de Chat	A unilateral jump while travelling, taking-off from one leg and landing on both in 5th position, in which the leading leg is extended in front and the rear leg is flexed underneath the hips while in the air.	1-to-2	0	Horizontal
Double Tour	A bilateral vertical jump from and to 5th position, in which the dancer will complete 720 degrees of rotational while in the air and switch the legs once.	2-to-2	0	Vertical
Jeté en Tournant	A unilateral jump while travelling, taking-off from one leg and landing on the other, in which the dancer rotates 360 degrees and splits the legs while in the air.	1-to-1	0	Horizontal
Grand pas Assemblé	A unilateral jump while travelling, taking-off from one leg and landing in 5th position	1-to-2	0	Horizontal
Saut de Basque	A unilateral jump while travelling, taking-off from one leg landing on the other leg, in which the dancer rotates 360 degrees with the leading leg extended and the rear leg flexed underneath the hips while in the air.	1-to-1	0	Horizontal

All jumps are completed in lower extremity external rotation. Some studies did not provide an operation defintion of the investigated jump; accordingly, the authors have extrapolated based on knowledge of classical ballet terminology (e.g., *Pas Jeté*)

Appendix B. Ethical Approval for Chapter 3

Reference: SMEC_2019-20_033

Name of proposer(s)	Adam Mattiussi Joseph Shaw
Name of supervisor	Jamie Tallent Phil Price Charlie Pedlar Matt Springham
Programme of study	PhD
Title of project	Injury Surveillance and Rehearsal Workload of a Professional Classical Ballet Company Over 5 Seasons

Supervisors, please complete section 1. If approved at level 1, please forward a copy of this Approval Sheet to the Faculty Ethics Representative for their records.

SECTION 1: To be completed by supervisor.			
☐ Approved at Level 1. ☒ Refer to Faculty Ethics Representative for consideration at Level 2 or Level 3.			
Signature of Supervisor (for student research projects):		Date:	28/08/2020

SECTION 2: To be completed by Faculty Ethics Representative.			
☒ Approved at Level 2. ☐ Level 3 consideration is required by Ethics Sub-Committee.			
Signature of Faculty Ethics Representative:		Date:	01/09/2020

Appendix C. Ethical Approval for Chapters 5 to 8

Reference: SMU_ETHICS_2020-21_151

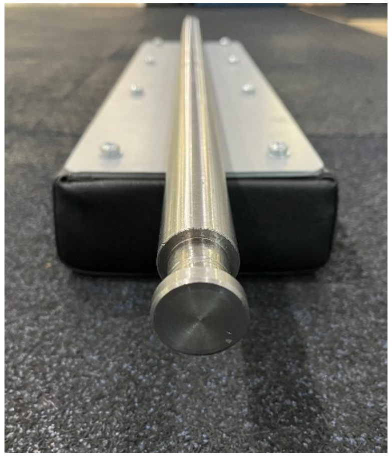
Name of proposer(s)	Adam Mattiussi Joseph Shaw
Name of supervisor	Jamie Tallent Phil Price Charlie Pedlar Matt Springham
Programme of study	PhD
Title of project	Kinetics and kinematics during jumping in professional ballet dancers

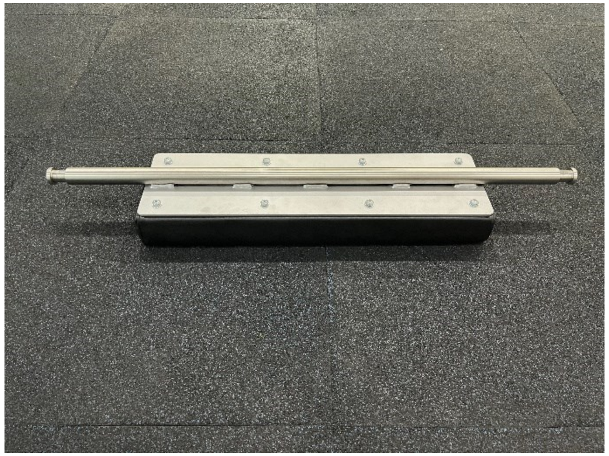
Supervisors, please complete section 1. If approved at level 1, please forward a copy of this Approval Sheet to the Faculty Ethics Representative for their records.

SECTION 1: To be completed by supervisor.			
☐ Approved at Level 1. ☒ Refer to Faculty Ethics Representative for consideration at Level 2 or Level 3.			
Signature of Supervisor (for student research projects):		Date:	25/09/20

SECTION 2: To be completed by Faculty Ethics Representative.			
☒ Approved at Level 2. ☐ Level 3 consideration is required by Ethics Sub-Committee.			
Signature of Faculty Ethics Representative:		Date:	3 February 2021

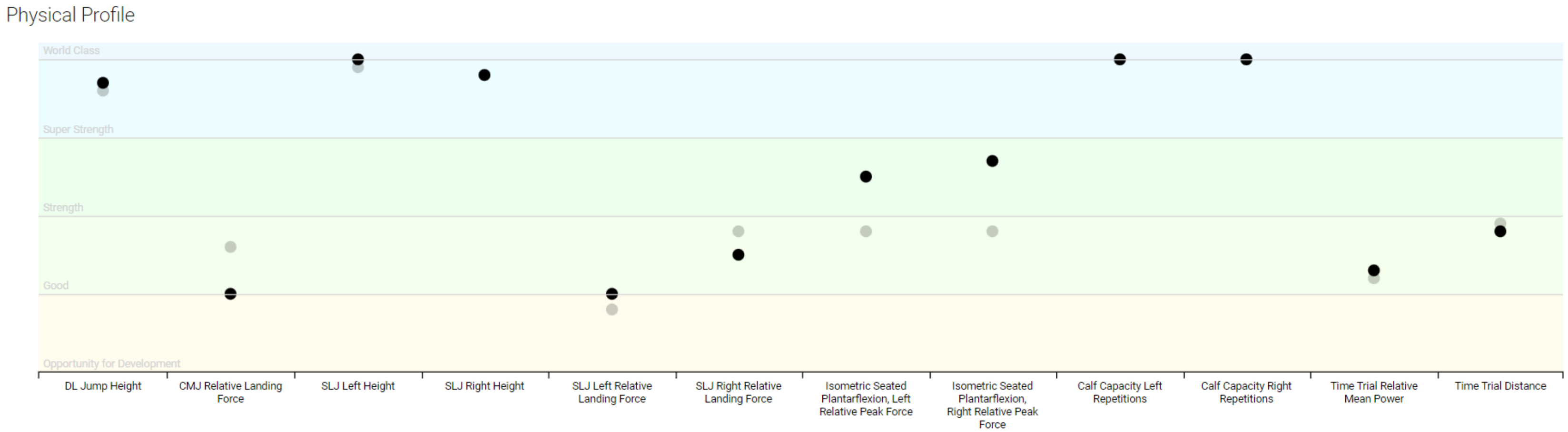
Appendix D. A Bespoke Barbell for Seated Isometric Force Testing





This barbell was designed and fabricated following the conclusion of Chapter 5 to improve comfort during seated isometric force tests. Although not used for data collection during this thesis it is now used for all seated isometric force tests at The Royal Ballet and has improved the comfort and buy-in from dancers undertaking the test. Subsequently, other organisations have adopted this barbell, such as the UK Sports Institute's Intensive Rehab Unit.

Appendix E. The Integration of Reference Data into an Applied Environment



Utilising a multidisciplinary approach, I integrated the reference isometric force data into a dancer development dashboard. The physical profile of a dancer was illustrated cross-sectionally to provide an overview of their strengths and weaknesses, followed by a longitudinal summary to illustrate change over time. Within this, the minimal detectable change data are integrated and conditionally formatted to simplify the interpretation of repeated measures. The purpose of this integration was to support the wider multidisciplinary team and ensure all practitioners had a shared vocabulary around dancer targets.