Nagy, Philip, Brogden, Christopher and Greig, Matt (2021) Isokinetic ankle eversion and inversion strength profiling of female ballet dancers. Journal of Sports Sciences, 39 (1). pp. 1-9.

Isokinetic Ankle Eversion and Inversion Strength Profiling of Female Ballet Dancers

Philip Nagy[1*], Chris Brogden[1], Matt Greig[1].

[1] *Department of Sport & Physical Activity, Edge Hill University, Ormskirk, Lancashire, L39 4QPUnited Kingdom.*

Philip Nagy; Nagyp@edehill.ac.uk, 01695 584512
Chris Brogden; Brogdenc@edgehill.ac.uk, 01695 587344
Matt Greig; Greigm@edgehill.ac.uk; 01695 584848

[*] Corresponding Author. Department of Sport & Physical Therapy, Edge Hill University, Ormskirk, Lancashire, United Kingdom. L39 4QP.
E-mail address: Nagyp@edgehill.ac.uk.

Abstract

Ankle injuries are highly prevalent in ballet, with strength highlighted as a primary risk factor. To profile ankle strength, fourteen female ballet dancers (age: 19.29 ± 1.59 years) completed an isokinetic testing protocol comprising concentric eversion (CON_{EV}) and inversion (CON_{INV}), and, eccentric inversion (ECC_{INV}) trials at four angular velocities ($30°\cdot s^{-1}$, $60°\cdot s^{-1}$, $90°\cdot s^{-1}$, $120°\cdot s^{-1}$) for both the dominant and non-dominant limb. In addition to Peak Torque (PT) and the corresponding Dynamic Control Ratios (DCRs), angle-specific derivatives of strength (AST) and Functional Range (FR) were calculated. There was no evidence of any significant bilateral strength asymmetry ($p = 0.90$) across all metrics, and no significant interactions with limb and contraction mode or velocity. A significant main effect for contraction mode ($p = 0.001$) highlighted greater ECC_{INV} – which was maintained with increasing isokinetic velocity – in contrast to reductions in CON_{EV} and CON_{INV} strength. Specifically, dancers are ECC_{INV} dominant at angular velocities greater than $60°\cdot s^{-1}$, which is likely to be characteristic of most functional tasks. The lack of bilateral asymmetry may be attributed to dance training interventions that facilitate bilateral development, but ipsilateral mode and velocity specific asymmetries have implications for injury risk and the training needs of female ballet dancers.

Key words: Dancers, Female athletes, Ankle injury, Joint strength, Isokinetic dynamometer.

1. Introduction

Ballet is a compound of artistry and athleticism demanding an intermittent locomotor profile of lower intensity activity interspersed with multiple, explosive jump-landing manoeuvres (Hincapie, Morton & Cassidy, 2008). The mechanical complexity and rigorous nature of ballet is routinely associated with injury risk, reported to affect between 13%-100% of dancers (Comin, Cook, Malliaras, McCormack, Calleja, Clarke & Connell, 2013; Negus, Hopper & Briffa, 2005). Injury incidence rates have been shown to range between 0.4-4.8 per 1000 hours of dance exposure (Smith, Gerrie, Varner, McCulloch, Lintner & Harris, 2015), with comparable trends for gender and training status. Female and male amateur dancers sustain 1.77 and 2.12 injuries/1000 dance hours compared with 1.06 and 1.46 in the professional cohort, respectively (Smith et al, 2015). Of all injuries sustained in ballet, between 59%-93% are to the lower extremities (Bowerman Whatman, Harris, Bradshaw & Karin, 2014; Ramkumar, Farber, Arnouk, Varner & McCulloch, 2016), with the ankle reported to be the most commonly injured location (Smith et al, 2015).

The mechanism for ankle trauma typically involves an inverted and plantar-flexed foot configuration (Skazalski, Kruczynski, Bahr, Bere, Whiteley & Bahr, 2017), inherent to the multi-directional jump-landing manoeuvres performed repeatedly by dancers. Whilst the mechanism of injury is well corroborated, the aetiological understanding is incomplete given the multi-faceted nature of the associated risk factors. Of the numerous modifiable, intrinsic risk factors for injury, functional deficits in strength has been routinely purported. (Baumhauer, Alosa, Renstrom, Trevino & Beynnon, 1995; Murphy, Connolly & Beynnon, 2003; Willems, Witvrouw, Delabere, Mahieu, De Bourdeaudhuij & De Clercq, 2005). The strength of the peroneal musculature is integral to stabilising the ankle complex and may facilitate reduced risk of ligamentous injury by resisting coronal-plane forces (Fox, Docherty, Schrader & Applegate, 2008). The gold-standard measure of ankle strength involves isokinetic dynamometry, but previous assessments of isokinetic ankle strength in dancers have been restricted to plantar/dorsiflexion protocols (Thomas & Parcel, 2004; Schmitt, Kuni & Sabo, 2005; Kenne & Unnithan, 2008). Negating the inversion movement commonly associated with ankle injury mechanism, and the movement profile of dance, limits the functional relevance of previous applications which fail to inform the explicit strength training needs of dancers.

Isokinetic assessments of ankle eversion and inversion strength have been conducted on non-dance populations, utilising angular velocities of $30°\cdot sec^{-1}$ and $120°\cdot sec^{-1}$ (Willems, Witvrouw, Verstuyft, Vaes & De Clercq, 2002; Pontaga, 2004). These speeds appear to be selected arbitrarily to represent slow and fast motions, but without rationale provided by the authors. Isokinetic data collection is defined by predetermined selection of contraction mode, range of motion and angular velocity, which should reflect the specific research question. Contentious issues also surround data analysis with respect to the resultant metrics of strength that are assessed and quantified. Peak torque is typically the primary outcome measure from isokinetic assessments but provides only a single maximum value with little consideration of the entire strength curve. Arguably, strength deficits are of greater value for interventions targeting injury prevention or performance enhancement. Contemporary research (Eustace, Page & Greig, 2017) has advocated the inclusion of additional outcome measures including functional range and angle-specific derivatives of strength, assessed over a range of angular velocities.

The aim of the current study was to evaluate ankle evertor and invertor strength capacity in female ballet dancers across a range of functionally relevant joint angles and angular velocities.

Limb dominance was also considered given that a typical choreograph may contain up to 200 jumps, of which 56% involve one-footed landings (Liederbach, Dilgen & Rose, 2006). Further, dancers may have a preferred limb for ‘pushing off’, jumping, or landing (Murphy, Connolly & Beynnon. 2003). The asymmetric movement sequence of a dance routine highlights the importance of bilateral symmetry in the lower limbs to decrease the risk of injuries attributed to compromised movement technique and posture (Croisier, Ganteaume, Binet, Genty & Ferret, 2008, Fousekis, Tsepis & Vagenas, 2010; Menzel, Chagas, Szmuchrowski, Araujo, de Andrade & de Jesus-Moraleida, 2013). A comprehensive profile of ankle eversion and inversion strength that considers bilateral asymmetry in addition to ipsilateral mode and speed-specific asymmetries, will inform clinical interpretation of the training needs required in this cohort.

2. Methods and Methods

2.1 Subjects

A cohort of 14 female amateur ballet dancers (age: 19.29 ± 1.59 years; height: 1.65 ± 0.05 metres; body mass: 61.00 ± 8.29 kilograms) were recruited to participate in the study. A random stratified sampling method was deployed to recruit participants from exiting institutional undergraduate dance populations, indicating that all participants were aged 18+. Stringent inclusion criteria dictated that participants were not dancing for a professional organisation. Further, all dancers had a minimum of 8 years dancing experienced and were required to be attending ballet training for a minimum of three hours per week. Participants were unable to participate in the study if they had sustained an injury in the 3 months prior to their testing session or were categorised as having ankle instability based on completion of the Cumberland Ankle Instability Tool (CAIT) questionnaire. The current study was approved by the institute’s departmental ethics committee, and, in accordance with the Declaration of Helsinki, all participants obtained a study information sheet and provided written informed consent prior to data collection.

2.2 Procedures

All participants were required to attend the Musculoskeletal Laboratory for one experimental testing session. Participants initially completed a standardized warm-up targeting ankle joint mobilisation. Ballet-specific exercises – 10 x Plié, 10 x Relevé (heel raise) – were completed in accordance with the constructs of a warm-up preceding a typical ballet class, and were followed by 10 slow eversion and inversion repetitions for both limbs (seated with legs outstretched) in reference to the subsequent isokinetic protocol. Five sub-maximal (50% effort) familiarisation trials of concentric ankle eversion (CON_{EV}) and inversion CON_{INV}), and, eccentric ankle inversion (ECC_{INV}) at all experimental testing velocities were completed as part of the warm-up protocol. The familiarisation trials were completed with progressive increments in angular velocity through the sequence; $30°\cdot s^{-1}$, $60°\cdot s^{-1}$, $90°\cdot s^{-1}$, and $120°\cdot s^{-1}$ for both limbs. Experimental trials were subsequently completed following a five-minute rest period, with five maximal repetitions for each contraction mode and speed.

2.2.1 Isokinetic strength assessment

Bilateral isokinetic ankle muscle strength was determined using an isokinetic dynamometer (System 4 pro, Biodex Medical Systems, Shirley, New York, USA) following manufacturer-recommended calibration. Each participant was asked to identify a preferred limb for which to land on during a unilateral ballet-specific jump landing task, in accordance with previous methods (Mertz and Docherty, 2012; Carcia, Cacolice & McGeary, 2019). For the purposes of the current investigation, the preferred limb is classified as the dominant limb hereafter. Each participant was positioned according to manufacturer's guidelines for ankle eversion/inversion strength assessment (dynamometer orientation, 0°; dynamometer tilt, 50°; seat orientation 90°; seatback tilt, 70°). A goniometer was used to set the foot attachment in 20° of plantarflexion to partially replicate the orientation of the foot when landing from a jump during a dance routine. Each participants' foot was secured to the ankle eversion/inversion footplate attachment using Velcro straps, whilst an additional dynamometer attachment positioned at the mid portion of the posterior thigh provided support to the testing limb. To further stabilize and isolate the ankle joint, Velcro straps were also applied across the chest, and the mid portion of the anterior thigh of the uninvolved limb. From a neutral position (vertical alignment of the foot), and to standardize the test protocol for all participants, ankle eversion and inversion motion limits were set at 20° resulting in an overall 40° range of motion.

Initiated at a position of max inversion (20°), all participants completed five maximal concentric ankle eversion and inversion trials (Sekir, Yildiz, Hazneci, Ors & Aydin, 2007), at angular velocities of $90°\cdot s^{-1}$, $60°\cdot s^{-1}$, $120°\cdot s^{-1}$and $30°\cdot s^{-1}$ for both limbs, in accordance with recommendations (Fish, Milligan & Killey, 2014). The non-linear order was chosen to minimise any potential learning effect. The same procedure was then completed for the eccentric ankle inversion trials. Concentric ankle eversion and inversion trials at each angular velocity were interspersed with a one-minute rest period, whilst 10-minutes rest separated ipsilateral concentric and eccentric trials to minimise the accumulation of fatigue (Yuksel, Ozgurbuz, Ergun, Islegen, Taskiran, Deneral & Ertat, 2011). No performance feedback was presented during any of the experimental trials.

2.3 Data Processing

Raw torque-angle time history data from each limb, contraction mode and angular velocity were exported to Excel (Microsoft Corporation, Washington, USA) for further analysis. With torque overshoot removed, the isokinetic phase of each repetition was determined, and the repetition producing the highest torque was analysed. At each velocity and mode of contraction, Peak Torque (PT), corresponding Angle of Peak Torque (APT), and Functional Range (FR – defined as the range over which 85% of peak torque is maintained) were established. Angle-Specific Torque (AST) data were calculated in 5° increments across the entire angular range (40°) for all angular velocities and contraction modes. Corresponding Dynamic Control Ratios (DCRs) were defined using PT (DCR_{PT}) and AST (DCR_{AST}) values.

2.4 Statistical Analysis

Descriptive statistics are presented as mean ± standard deviation (σ). The distribution of data was quantified using histograms, Q-Q plots, skewness and kurtosis, and the Shapiro-Wilk statistic. With the data normality assumption satisfied, linear mixed models were employed to examine bilateral isokinetic strength differences in each outcome measure across all testing velocities and contraction modes. Bonferroni-corrected post-hoc pairwise comparisons for significant main effects and interactions were determined as required, and 95% confidence intervals (CI) and Cohen's *d* effect sizes (small, 0.20-0.49; moderate, 0.50-0.79; large > 0.80) were also presented. Alpha was determined a priori and deemed statistically significant at the $p < 0.05$ level for all outcome measures. Statistical analyses were conducted using IBM SPSS statistics V25.0 software (IBM, Armonk, New York, USA).

3. Results

3.1 Peak torque

Figure 1 summarises the influence of contraction mode and angular velocity on bilateral PT. There was no significant main effect for limb ($p = 0.35$), nor any significant limb*contraction mode ($p = 0.72$), limb*angular velocity ($p = 0.96$), or limb*contraction mode*angular velocity ($p = 1.00$) interaction. Significant main effects for contraction mode ($p = 0.001$) and angular velocity ($p = 0.001$) were identified, along with a significant contraction mode*angular velocity interaction ($p = 0.001$). For instances where the main effect/interactions involving limb are not significant, corresponding values for significant contraction mode, angular velocity and angle main effects/interactions represent an average from the dominant and non-dominant limb and this is consistent throughout. Figure 1 demonstrates that $\mathrm{ECC_{INV}}$ PT was significantly greater than $\mathrm{CON_{EV}}$ and $\mathrm{CON_{INV}}$ at $60°\cdot s^{-1}$ ($p = 0.001$, $d = 0.43$-0.48), $90°\cdot s^{-1}$ ($p = 0.001$, $d = 0.67$-0.73) and $120°\cdot s^{-1}$ ($p = 0.001$, $d = 0.73$-0.77).

****INSERT FIGURE 1 HERE****

3.2 Angle of peak torque

Table 1 displays bilateral APT data for all contraction modes and velocities. No significant main effect for limb ($p = 0.82$) was obtained, nor was there any significant limb*contraction mode ($p = 0.46$), limb*angular velocity ($p = 0.55$), or limb*contraction mode*angular velocity ($p = 0.89$) interaction. Analyses revealed a significant main effect for contraction mode ($p = 0.001$) with $\mathrm{ECC_{INV}}$ APT (27.10° ± 7.16°; CI: 25.83-28.50) occurring significantly later in the range of motion compared with $\mathrm{CON_{EV}}$ (18.45° ± 6.1°; CI: 17.20-19.70, $p = 0.001$, $d = 0.55$) and $\mathrm{CON_{INV}}$ (16.62° ± 6.46°; CI: 15.37-17.88, $p = 0.001$, $d = 0.61$) irrespective of angular velocity. A significant main effect for angular velocity ($p = 0.02$) demonstrated that APT was achieved significantly earlier at $30°\cdot s^{-1}$ (18.83° ± 9.03°, CI: 17.36-20.29) compared with $90°\cdot s^{-1}$ (22.17° ± 7.56°; CI: 20.70-23.63, $p = 0.01$, $d = 0.19$) irrespective of contraction type. No significant contraction mode*angular velocity ($p = 0.27$) interaction was observed.

****INSERT TABLE 1 HERE****

3.3 Functional range

Figure 2 illustrates the influence of contraction mode angular velocity on bilateral FR There was no significant main effect for limb ($p = 0.10$), and no significant limb*contraction mode ($p = 0.66$), limb*angular velocity ($p = 1.00$), or limb*contraction mode*angular velocity ($p = 0.96$) interaction. No significant main effect for contraction mode ($p = 0.15$) was found, however a significant main effect for angular velocity ($F = 17.37$, $p = 0.001$) was revealed irrespective of contraction mode. FR at $30°\cdot s^{-1}$ (18.67° ± 5.95°; CI: 17.56-19.79) was significantly lower than at $60°\cdot s^{-1}$ (21.06° ± 5.01°; CI: 19.99-22.22; $p = 0.02$, $d = 0.20$) but significantly higher compared with $120°\cdot s^{-1}$ (15.82° ± 6.27°; CI: 14.15-16.47; $p = 0.001$, $d = 0.22$). FR at $60°\cdot s^{-1}$ was significantly greater than at $120°\cdot s^{-1}$ ($p = 0.001$, $d = 0.41$), and at $90°\cdot s^{-1}$ (19.38° ± 5.35°; CI: 18.21-20.44) compared with $120°\cdot s^{-1}$ ($p = 0.001$, $d = 0.29$). The significant contraction mode*angular velocity interaction (p = 0.001) demonstrated that ECC_{INV} FR was significantly greater at than CON_{EV} and CON_{INV} at $30°\cdot s^{-1}$ (p = 0.001, *d* = 0.46-0.57), but significantly lower at $120°\cdot s^{-1}$ (p = 0.001, *d* = 0.67-0.73).

****INSERT FIGURE 2 HERE****

3.4 Dynamic control ratios calculated from PT data.

DCR_{PT} values are presented in Table 2. There was no significant main effect for limb (p = 0.90), nor a significant limb*contraction mode (p = 0.15), limb*angular velocity (p = 0.75) 0.05), or limb*contraction mode*angular velocity (p = 0.98) interaction. Significant main effects for contraction mode (p = 0.001) and angular velocity (p = 0.001), and the corresponding contraction mode*angular velocity interaction (p = 0.01) were highlighted. There was no indication of any contraction mode*angular velocity interactions at $30°\cdot s^{-1}$, however $\text{CON}_{\text{EV}}:\text{CON}_{\text{INV}}$ dynamic control ratios were significantly greater than $\text{CON}_{\text{EV}}:\text{ECC}_{\text{INV}}$ and $\text{CON}_{\text{INV}}:\text{ECC}_{\text{INV}}$ at $60°\cdot s^{-1}$ (p = 0.01, *d* = 0.38-0.49), $90°\cdot s^{-1}$ (p = 0.001, *d* = 0.70-0.77) and $120°\cdot s^{-1}$ p = 0.001, *d* = 0.74-0.78) respectively.

****INSERT TABLE 2 HERE****

3.5 Angle-specific Torque

Figure 3 depicts the influence of contraction mode, angular velocity, and angle on bilateral AST. There was no significant main effect for limb (p = 0.59), nor a significant interaction for limb*contraction mode (p = 0.86), limb*angle (p = 1.00) limb*angular velocity (p = 0.95), limb*contraction mode*angle (p = 1.00), limb*contraction mode*angular velocity (p = 0.68), limb*angle*angular velocity (p = 1.00), or limb*contraction mode*angle*angular velocity (p = 1.00) interaction. Significant main effects for contraction mode (p = 0.001), angle (p = 0.001), and angular velocity (p = 0.001), and, significant contraction mode*angle (p = 0.001), and contraction mode*angular velocity (p = 0.001) were identified. Analyses revealed that ECC_{INV} torque was significantly greater than the two concentric modes for angles ≥ 15° during the $30°\cdot s^{-1}$, $60°\cdot s^{-1}$ and $90°\cdot s^{-1}$ trials, and for angles ≥ 25° during $120°\cdot s^{-1}$ (see figure 3).

****INSERT FIGURE 3 HERE****

3.6 Dynamic control ratios derived from AST data.

Table 3 summarises the effect of angle and angular velocity on the respective bilateral DCR_{AST}. There was no significant main effect for limb (p = 0.58), nor a significant limb *contraction mode (p = 0.08), limb*angle (p = 1.00), limb*angular velocity (p = 0.17), limb*contraction mode*angle (p = 1.00), limb*contraction mode*angular velocity (p = 0.47), limb*angle*angular velocity (p = 1.00), or limb*contraction*mode*angle*angular velocity (p = 1.00) interaction. However, significant main effects for contraction mode (p = 0.001), angle (p = 0.01) and angular velocity (p = 0.001) were identified, along with a significant contraction mode*angle (p = 0.001) and contraction mode*angular velocity (p = 0.02) interaction. At angles ≥15°, CON_{EV}:CON_{INV} dynamic control ratios were significantly higher than CON_{EV}:ECC_{INV} and CON_{INV}:ECC_{INV}. Moreover, CON_{EV}:CON_{INV} dynamic control ratios were also significantly greater than the ECC_{INV}-inclusive ratios at all isokinetic speeds (see table 3). There was no significant angle*angular velocity (p = 0.59) or contraction mode*angle*angular velocity (p = 0.97) interaction.

****INSERT TABLE 3 HERE****

4. Discussion

Strength deficits have been implicated as a modifiable risk factor for ankle injury, a prevalent injury in ballet (Willems et al, 2005; Smith et al, 2015). Contrary to previous research, the present study focused strength profiling on the ankle eversion/inversion mechanism that is fundamental to the physical demands of ballet and the common mechanism of injury. Main effects for limb dominance were investigated for all isokinetic outcome measures in consideration of the aesthetic demand for movement symmetry within choreographed routines. There was no evidence of bilateral asymmetry in any of the isokinetic ankle strength measures. During a dance choreograph, a performer is presumed to execute technical intricacies using each leg equally, and therefore, technique/rehearsal classes are assumed to facilitate bilateral development (Farrar-Baker & Wilmerding, 2006). A key responsibility for the ankle joint is to attenuate resultant mechanical loads following contact with the ground, to which strength plays a pivotal role. With over half of jumps during a typical routine requiring a unilateral landing component (Mertz & Docherty, 2012), symmetry between limbs is desirable to minimise a greater loading and ensuing tendency to sustain injury in a particular side. The symmetry in isokinetic strength in this population may be attributed to an early emphasis on bilateral limb control in dance training, which may be crucial in developing equal bilateral strength, and reducing ankle injury risk (Bronner & Ojofeitimi, 2006). Dance injury epidemiology literature is not available to critically discuss this finding in relation to injury risk, however bilateral and ipsilateral isokinetic strength discrepancies have been associated with an increased injury risk (Croisier et al, 2008).

Potential strength imbalances were also considered in respect to contraction mode and movement speed. The contraction mode*angular velocity interaction demonstrated that ECC_{INV} strength was significantly greater than CON_{EV} and CON_{INV} at all but the slowest angular velocity, with implications for DCRs. This observation is consistent with the classic force-velocity profile comprising each contraction type, in that concentric strength typically reduces as a product of increasing angular velocity, whereas eccentric strength remains relatively constant (Cress, Peters & Chandler, 1992). The higher values observed for ECC_{INV} strength at the greater angular velocities – which arguably have better functional relevance with regards to dance performance - may be crucial in preventing the inverted foot alignment mechanism common to ankle sprain incidence (Kaminski, Buckley, Powers, Hubbard & Ortiz, 2003).

The FR metric provides insight on the profile of the strength curve, with higher values indicative of the ability to maintain >85% of PT for a greater range of motion. In this study, FR was defined at 85% of PT based on observations that a 15% reduction in PT increases injury risk (Croisier et al, 2008). Although this data is not available in a dance population, consideration of the FR metric in isokinetic strength analyses may prove vital in identifying markers for injury. At the slower velocities (30°·s^{-1} and 60°·s^{-1}), ECC$_{\mathrm{INV}}$ FR was higher than both concentric modes. However, an inverse trend was established in the contraction mode*angular velocity interaction at faster velocities (90°·s^{-1} and 120°·s^{-1}), whereby CON$_{\mathrm{EV}}$ and CON$_{\mathrm{INV}}$ FR decreased marginally relative to the significant reductions demonstrated for ECC$_{\mathrm{INV}}$. In accordance with ankle injury aetiology (Skazalski et al, 2017) and the performance characteristics of dance (Twitchett, Koutedakis & Wyon, 2009), the notable decline in ECC$_{\mathrm{INV}}$ FR at higher velocities may have implications on injury susceptibility when executing dance-specific locomotion. Lower ECC$_{\mathrm{INV}}$ strength may compromise the ability to resist inversion forces thereby proliferating injury risk (Fox et al, 2008). Rather than using PT – which provides a single strength value for a pre-determined range of motion – in the pursuit of identifying markers for injury, professionals with an injury reduction focus may benefit from the FR metric during isokinetic strength testing. The significant reductions in ECC$_{\mathrm{INV}}$ FR at angular velocities exceeding 60°·s^{-1} provides a focus for subsequent strength training interventions. Even if PT and the maxima of strength curve is unchanged, a reduction in FR suggests a decrease in strength away from the single joint angle defined as APT. Practically, a dancer would benefit from high PT and FR since performance demands will move through an angular range at the ankle. However, it should be acknowledged that a decrease in FR across all contraction modes at higher velocities may be indicative of a limited isokinetic phase as the dynamometer crank arm accelerates to higher speeds over a relatively small range of motion. Torque may indeed be maintained at 85% of PT outside the isokinetic range, but the restricted focus on the isokinetic data curtails the FR metric. The range of movement for ankle eversion and inversion is smaller than knee flexion/extension for example (Eustace et al, 2017), and thus, FR values appear to be joint specific and should be interpreted with this in mind. Moreover, direct comparisons of FR between relevant studies may only be achievable when uniform methodological designs are used.

Conventional DCRs are derived from PT values without any consideration of the angle at which PT is achieved, and thus, limit an understanding of how strength changes as a function of angle. Data from the current investigation demonstrated that Peak CON$_{\mathrm{EV}}$ and CON$_{\mathrm{INV}}$ torque was achieved at ~18° (2° of inversion) and ~17° (3° of eversion), thereby representing a relatively neutral foot alignment over the 40° range of motion. ECC$_{\mathrm{INV}}$ PT occurred significantly later at ~27°, representing a 7° position of inversion. Previous literature has failed to quantify the angle of peak torque for ankle inversion/eversion isokinetic strength ratios, preventing direct comparison. However, studies examining strength parameters at the knee joint have demonstrated that APT varies between concentric and eccentric modes of contraction and across a range of angular velocities (Cohen, Zhao, Okwera, Matthews & Delextrat, 2015; Eustace et al, 2017). The evident inconsistencies for APT from the current study and indeed other investigations, raises questions over the value of traditional PT-derived strength ratios and supports the inclusion of AST assessed across a number of angular velocities. The greater PT but smaller FR in ECC$_{\mathrm{INV}}$ at higher velocities has implications for functional performance and the strategies deployed in training and/or rehabilitation. The inverted configuration in ECC$_{\mathrm{INV}}$ – approximately 7° – compared with concentric modes may serve as a protective mechanism against ankle injury during execution of dance-specific movement, in which the foot is frequently loaded into inversion (O'Loughlin, Hodgkins & Kennedy, 2008).

Findings from the study revealed significant main effects for contraction mode, angle, and angular velocity on AST, whilst significant contraction mode*angle and contraction mode*angular velocity interactions were also revealed. Data for AST and corresponding controls ratios were significantly higher for ECC_{INV} than CON_{EV} and CON_{INV}, with more profound differences observed at the latter ranges of the movement, and with increasing angular velocity. This finding may be attributed to both the force-velocity and force-angle relationships between contraction modes. CON_{EV} and CON_{INV} strength portray a quadratic trend, in which PT is achieved at approximately midpoint of the movement, whereas ECC_{INV} PT is achieved towards end range. The use of angle-specific torque is sensitive to the changes in strength at various positions within a movement. Resultant DCRs may be used in the screening of performers towards injury reduction, and in the management of injury during rehabilitation. For example, in the current study, whilst decreases in CON_{INV} strength near to full ankle inversion were exacerbated as angular velocity increased, ECC_{INV} was relatively consistent. ECC_{INV} dominance at the end ranges of movement and at higher velocities may indeed reduce the likelihood of ankle injury when executing the jump-landing, cutting manoeuvres of a dance routine.

Caution ought to be taken when generalising these findings beyond the specific experimental design employed. Isokinetic testing protocols have some inherent methodological constraints, which should be considered when developing the data collection paradigm. The joint range of motion and joint angular velocities used in the current study are close to the physiological capabilities of the ankle when tested in this restricted state. Pilot testing highlighted that no isokinetic phase was determined at angular velocities of $\geq 150°\cdot s^{-1}$, and the range of motion is prescribed using passive movement of the joint. Consequently, this passive manipulation of the joint within an isokinetic testing paradigm may not reflect the physical capacity of the joint during active movement. In the current investigation, limb dominance was determined using a prospective classification based on preference to ballet-specific tasks. Carcia et al. (2019) highlighted that limb dominance was task-specific, and thus, our approach is specific to the participants and focus of our study. The use of alternative classifications of limb dominance, including retrospective classification based on outcome measures, and the impact on interpretation of the findings warrants future research. The present study focused on ankle eversion/inversion strength given its mechanical associations with injury. However, a strength profile of dancers may include plantar/dorsiflexion strength in light of kinematic analyses highlighting ankle injuries to occur in neutral (Fong, Chan, Mok, Yung, & Chan, 2009) and dorsi-flexed positions (Kristianslund, Bahr, & Krosshaug, 2011). Kinematic analyses of injury incidence or dance-specific movements may inform bespoke isokinetic testing protocols but must also account for physical limitations of the ankle during such assessments. Further research is required in the associations between isokinetic metrics and injury incidence, which may inform a threshold for the calculation of FR. Contemporary analysis metrics that delve beyond the highest value of a strength curve are advocated. Data collection ought to utilise the capacity of the isokinetic dynamometer to measure net joint torque at predetermined angles and angular velocities to provide a screening battery of greatest functional relevance to the sport.

5. Conclusions

This is the first study to consider the eversion/inversion strength of female ballet dancers, with previous literature considering only plantar/dorsiflexion despite the influence of inversion on ankle injury mechanics. Findings from the current study demonstrate bilateral symmetry in female dancers during a comprehensive isokinetic ankle strength testing protocol. This observation may be attributed to both appropriate training interventions from an early age, and, regular exposure to the asymmetric movement patterns of dance that facilitates bilateral development. The isokinetic strength profile of dancers in this study illustrated that ECC_{INV}

strength is maintained over a range of angular velocities, compared with reductions in CON_{EV} and CON_{INV} strength as movement speed increases. Specifically, dancers appear to be ECC_{INV} dominant at angular velocities of $60°·s^{-1}$ and beyond, and for all angular displacements providing implications for functional performance and injury risk. Beyond the singular peak of the torque-angle curve, ECC_{INV} had greater FR at velocities $<90°·s^{-1}$ compared with the concentric modes, which may indicate a protective mechanism for injury. The results and methods highlighted within this study provide medical practitioners with the opportunity to produce a comprehensive isokinetic strength profile of dancers. This information can be used to help enhance understanding of injury occurrence, whilst producing more detailed information for a dancers return to performance.

Acknowledgement

The authors express thanks to the participants involved in the study.

Ethical approval

Approval of this study was granted by the University’s departmental ethics committee.

Funding

This study received no funding from any organisation.

Disclosure of interest

The authors report no conflict of interest.

References

BAUMHAUER, J. F., ALOSA, D. M., RENSTROM, P. A. F. H., TREVINO, S. and BEYNNON, B., 1995. A Prospective Study of Ankle Injury Risk Factors. *The American Journal of Sports Medicine*. 23 (5), pp. 564-570.

BOWERMAN E., WHATMAN, C., HARRIS, N., BRADSHAW, E. and KARIN, J., 2014. Are maturation, growth and lower extremity alignment associated with overuse injury in elite adolescent ballet dancers? *Physical Therapy in Sport*. 15 (4), pp. 234-241.

BRONNER, S. and OJOFEITIMI, S., 2006. Gender and Limb Difference in Healthy Elite Dancers: Passé Kinematics. *Journal of Motor Behaviour*. 38 (1), pp. 71-79.

CARCIA, C. R., CACOLICE, P. A. and MCGEARY, S., 2019. Defining Lower Extremity Dominance: The Relationship between Preferred Lower Extremity and Two Functional Tasks. *International Journal of Sports Physical Therapy*. 14 (2), pp. 188-191.

COHEN, D. D. ZHAO, B., OKWERA, B., MATTHEWS, M. J. and DELEXTRAT, A., 2015. Angle-specific eccentric hamstring fatigue after simulated soccer. *International Journal of Sports Physiology and Performance*. 10 (3), pp. 325-331.

COMIN, J., COOK, J. L., MALLIARAS, P., MCCORMACK, M., CALLEJA, M., CLARKE, A. and CONNELL, D., 2013. The prevalence and clinical significance of sonographic tendon abnormalities in asymptomatic ballet dancers: a 24-month longitudinal study. *British Journal of Sports Medicine*. 47 (2) pp. 89-92.

CRESS, N. M., PETERS, K. S. and CHANDLER, J. M., 1992. Eccentric and Concentric Force-Velocity Relationships of the Quadriceps Femoris Muscle. *Journal of Orthopaedic & Sports Physical Therapy*. 16 (2), pp 82-86.

CROISIER, J. L., GANTEAUME, S., BINET, J., GENTY, M. and FERRET, J-M., 2008. Strength imbalances and prevention of hamstring injuries in professional soccer players: a prospective study. *American Journal of Sports Medicine*. 36 (8), pp. 1469-1475.

EUSTACE, S. J., PAGE, R. M. and GREIG, M., 2017. Contemporary approaches to isokinetic strength assessment in professional football players. *Science and Medicine in Football*. 1 (3), pp. 251-257.

FARRAR-BAKER, A. and WILMERDING, V., 2006. Prevalence of lateral bias in the teaching of beginning and advanced ballet. *Journal of Dance Medicine and Science* 10 (3/4), pp. 81-85.

FISH, M., MILLIGAN, J. and KILLEY, J., 2014. Is it possible to establish reference values for ankle muscle isokinetic strength? A meta-analytical study. *Isokinetics and Exercise Science*. 22 (2), pp. 85-97.

FONG, D. T-K., CHAN, Y-Y, MOK, K-M., YUNG, P. S-H. and CHAN, K-M., 2009. Understanding acute ankle ligamentous sprain injury in sports. *Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology*. 1 pp. 1-14.

FOUSEKIS, K., TSEPIS, E. and VAGENAS, G., 2010. Lower limb strength in professional soccer players: profile, asymmetry, and training age. *Journal of Sports Science & Medicine*. 1 (9), pp. 364-373.

FOX, J., DOCHERTY, C. L., SCHRADER, J. and APPLEGATE, T., 2008. Eccentric Plantar-Flexor Torque Deficits in Participants With Functional Ankle Instability. *Journal of Athletic Training*. 43 (1), pp. 51-54.

HINCAPIE, C. A., MORTON, E. J. and CASSIDY, J. D., 2008. Musculoskeletal injuries and pain in dancers. *Archives of Physical Medicine and Rehabilitation*. 89 (9), pp. 1819-1829.

KAMINSKI, T. W., BUCKLEY, B. D., POWERS, M. E., HUBBARD, T. J. and ORTIZ, C., 2003. Effect of strength and proprioception training on eversion to inversion strength ratios in subjects with unilateral functional ankle instability. *British Journal of Sports Medicine*. 37 (5), pp. 410-415.

KENNE, E. and UNNITHAN, V. B., 2008. Knee and Ankle Strength and Lower Extremity Power in Adolescent Female Ballet Dancers. *Journal of Dance Medicine and Science*. 12 (2), pp. 59-65.

KRISTIANSLUND, E., BAHR, R. and KROSSHAUG, T., 2011. Kinematics and kinetics of an accidental lateral ankle sprain. *Journal of Biomechanics*. 44 (14), pp. 2576-2578.

LIEDERBACH, M., RICHARDSON, M., RODRIGUEZ, M., COMPAGNO, J., DILGEN, F. E. and ROSE, D. J., 2006. Jump exposures in the dance training environment. *Journal of Athletic Training*. 41 (2), S85.

MENZEL, H. J., CHAGAS, M. H., SZMUCHROWSKI, L. A., ARAUJO, S. R., DE ANDRADE, A. G. and DE JESUS-MORALEIDA, F. R., 2013. Analysis of Lower Limb Asymmetries by Isokinetic and Vertical Jump Tests in Soccer Players. *Journal of Strength & Conditioning Research*. 27 (5), pp. 1370-1377.

MERTZ, L. and DOCHERTY, C., 2012. Self-Described Differences Between Legs in Ballets Dancers: Do They Relate to Postural Stability and Ground Reaction Forces Measures? *Journal of Dance Medicine and Science*. 16 (4), pp. 154-161.

MURPHY, D. F. CONNOLLY, D. A. J. and BEYNNON, B. D., 2003. Risk factors for lower extremity injury a review of literature. *British Journal of Sports Medicine*. 37 (1), pp. 13-29.

NEGUS, V., HOPPER, D. and BRIFFA, K., 2005. Associations between Turnout and Lower Extremity Injuries in Classical Ballet Dancers. *Journal of Orthopaedic and Sports Physical Therapy*. 35 (5), pp. 307-318.

O'LOUGHLIN, P. F., HODGKINS, C. W. and KENNEDY, J. G., 2008. Ankle Sprains and Instability in Dancers. *Clinics in Sports Medicine*. 27 (2), pp. 247-262.

PONTAGA, I., 2004. Ankle joint evertor-invertor muscle torque ratios decrease due to recurrent lateral ligament sprains. *Clinical Biomechanics*. 19 (7), pp. 760-762.

RAMKUMAR, P. N., FARBER, J., ARNOUK, J., VARNER, K. E. and MCCULLOCH, P. C., 2016. Injuries in a Professional Ballet Dance Company: a 10-year Retrospective Study. *Journal of dance medicine and science*. 20 (1), pp. 30-37.

SCHMITT, H., KUNI, B. and SABO, D., 2005. Influence of Professional Dance Training on Peak Torque and Proprioception at the Ankle. *Clinical Journal of Sport Medicine*. 15 (5), pp. 331-340.

SEKIR, U., YILDIZ, Y., HAZNECI, B., ORS, F. and AYDIN, T., 2007. Effect of isokinetic training on strength, functionality and proprioception in athletes with functional ankle instability. *Knee Surgery, Sports Traumatology, Surgery*. 15 (5), pp. 654-664.

SKAZALSKI, C., KRUCZYNSKI, J, BAHR, M. A., BERE, T., WHITELEY, R. and BAHR, R., 2017. Landing-related ankle injuries do not occur in plantarflexion as once thought: a systematic analysis of ankle injuries in worldclass volleyball. *British Journal of Sports Medicine*. 51 (4), pp. 1-9.

SMITH, P. J., GERRIE, B. J., VARNER, K. E., MCCULLOCH, P. C., LINTNER, D. M. and HARRIS, J. D., 2015. Incidence and Prevalence of Musculoskeletal Injury in Ballet: A Systematic Review. *Orthopaedic Journal of Sports Medicine*. 3 (7), pp. 1-9.

THOMAS, K. S. and PARCELL, A. C., 2004. Functional Characteristics of the Plantar Flexors in Ballet Dancer, Folk Dancer, and Non-Dancer Populations. *Journal of Dance Medicine and Science*. 8 (3), pp. 73-77.

TWITCHETT, E. A., KOUTEDAKIS, Y. AND WYON, M., 2009. Physiological fitness and professional classical ballet performance. *Journal of Strength and Conditioning Research*. 23 (9), pp. 2732-2740.

WILLEMS, T., WITVROUW, E., VERSTUYFT, J., VAES, P., and DE CLERCQ, D., 2002. Proprioception and muscle strength in subjects with a history of ankle sprains and chronic instability. *Journal of Athletic Training*. 37 (4), pp. 487–493.

WILLEMS, T. M., WITVROUW, E., DELBAERE, K., MAHIEU, N., De BOURDEAUDHUIJ, L. and DE CLERCQ, D., 2005a. Intrinsic risk factors for inversion ankle sprains in male subjects: a prospective study. *American Journal of Sports Medicine*. 33 (3), pp. 415-423.

YUKSEL, O., OZGURBUZ, C., ERGUN, M., ISLEGEN, C., TASKIRAN, E., DENEREL, N. and ERTAT, A., 2011. Inversion/Eversion strength dysbalance in patients with medial tibial stress syndrome. *Journal of Sports Science & Medicine*. 10 (4), pp. 737-742.

Legend to Tables and Figures

Tables

Table 1. The influence of angular velocity, limb and mode of contraction on APT.

Table 2. The influence of limb and angular velocity on selected Dynamic Control Ratios calculated from PT. Values are mean ± σ.

Table 3. The influence of limb, angle and angular velocity on the corresponding DCR_{AST} data. Values are mean ± σ.

Figures

Figure 1. PT for each mode of contraction for the dominant (top) and non-dominant (bottom) limb. Values are mean ± σ. * denotes a significant difference between the eccentric and concentric-inclusive contraction modes.

Figure 2. FR for each mode of contraction for the dominant (top) and non-dominant (bottom) limb. Values are mean ± σ. * denotes a significant difference between the eccentric and concentric-inclusive contraction modes.

Figure 3. Angle-specific torque for each mode of contraction for the dominant (left) and non-dominant (right) limb. Values are mean ± σ. * denotes a significant difference for AST between the eccentric and concentric-inclusive contraction modes.