Nagy, Philip ORCID logoORCID:

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1	Isokinetic Ankle Eversion and Inversion Strength Profiling of Female Ballet Dancers
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3	Philip Nagy ¹ , Chris Brogden ¹ , Matt Greig ¹ .
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5	Department of Sport & Physical Activity, Edge Hill University, Ormskirk, Lancashire, L39
07	4QP United Kingdom.
/ Q	Dhilin Nagy: Nagyn@adahill.ac.uk 01605 584512
a	Chris Brogden: Brogdenc@edgehill.ac.uk 01695 587344
10	Matt Greig: Greigm@edgehill.ac.uk: 01695 584848
11	Watt Oferg, Ofergine edgeminae.uk, 01099 504040
12	* Corresponding Author, Department of Sport & Physical Therapy, Edge Hill University
13	Ormskirk, Lancashire, United Kingdom, L39 4OP.
14	<i>E-mail address:</i> Nagyp@edgehill.ac.uk.
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51 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 $(30^{\circ} \cdot s^{-1}, 60^{\circ} \cdot s^{-1}, 60^{\circ} \cdot s^{-1})$ $90^{\circ} \cdot s^{-1}$, $120^{\circ} \cdot s^{-1}$) 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 $60^{\circ} \cdot s^{-1}$, 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.

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

101 102 **1. Introduction**

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104 Ballet is a compound of artistry and athleticism demanding an intermittent locomotor profile 105 of lower intensity activity interspersed with multiple, explosive jump-landing manoeuvres 106 (Hincapie, Morton & Cassidy, 2008). The mechanical complexity and rigorous nature of ballet 107 is routinely associated with injury risk, reported to affect between 13%-100% of dancers 108 (Comin, Cook, Malliaras, McCormack, Calleja, Clarke & Connell, 2013; Negus, Hopper & 109 Briffa, 2005). Injury incidence rates have been shown to range between 0.4-4.8 per 1000 hours 110 of dance exposure (Smith, Gerrie, Varner, McCulloch, Lintner & Harris, 2015), with 111 comparable trends for gender and training status. Female and male amateur dancers sustain 112 1.77 and 2.12 injuries/1000 dance hours compared with 1.06 and 1.46 in the professional 113 cohort, respectively (Smith et al, 2015). Of all injuries sustained in ballet, between 59%-93% 114 are to the lower extremities (Bowerman Whatman, Harris, Bradshaw & Karin, 2014; 115 Ramkumar, Farber, Arnouk, Varner & McCulloch, 2016), with the ankle reported to be the 116 most commonly injured location (Smith et al, 2015).

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118 The mechanism for ankle trauma typically involves an inverted and plantar-flexed foot 119 configuration (Skazalski, Kruczynski, Bahr, Bere, Whiteley & Bahr, 2017), inherent to the 120 multi-directional jump-landing manoeuvres performed repeatedly by dancers. Whilst the 121 mechanism of injury is well corroborated, the aetiological understanding is incomplete given 122 the multi-faceted nature of the associated risk factors. Of the numerous modifiable, intrinsic 123 risk factors for injury, functional deficits in strength has been routinely purported. (Baumhauer, 124 Alosa, Renstrom, Trevino & Beynnon, 1995; Murphy, Connolly & Beynnon, 2003; Willems, 125 Witvrouw, Delabere, Mahieu, De Bourdeaudhuij & De Clercq, 2005). The strength of the 126 peroneal musculature is integral to stabilising the ankle complex and may facilitate reduced 127 risk of ligamentous injury by resisting coronal-plane forces (Fox, Docherty, Schrader & 128 Applegate, 2008). The gold-standard measure of ankle strength involves isokinetic 129 dynamometry, but previous assessments of isokinetic ankle strength in dancers have been restricted to plantar/dorsiflexion protocols (Thomas & Parcel, 2004; Schmitt, Kuni & Sabo, 130 131 2005; Kenne & Unnithan, 2008). Negating the inversion movement commonly associated with 132 ankle injury mechanism, and the movement profile of dance, limits the functional relevance of 133 previous applications which fail to inform the explicit strength training needs of dancers.

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135 Isokinetic assessments of ankle eversion and inversion strength have been conducted on nondance populations, utilising angular velocities of $30^{\circ} \cdot \sec^{-1}$ and $120^{\circ} \cdot \sec^{-1}$ (Willems, Witvrouw, 136 Verstuyft, Vaes & De Clercq, 2002; Pontaga, 2004). These speeds appear to be selected 137 138 arbitrarily to represent slow and fast motions, but without rationale provided by the authors. 139 Isokinetic data collection is defined by predetermined selection of contraction mode, range of 140 motion and angular velocity, which should reflect the specific research question. Contentious 141 issues also surround data analysis with respect to the resultant metrics of strength that are 142 assessed and quantified. Peak torque is typically the primary outcome measure from isokinetic 143 assessments but provides only a single maximum value with little consideration of the entire 144 strength curve. Arguably, strength deficits are of greater value for interventions targeting injury 145 prevention or performance enhancement. Contemporary research (Eustace, Page & Greig, 146 2017) has advocated the inclusion of additional outcome measures including functional range 147 and angle-specific derivatives of strength, assessed over a range of angular velocities.

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

151 Limb dominance was also considered given that a typical choreograph may contain up to 200 152 jumps, of which 56% involve one-footed landings (Liederbach, Dilgen & Rose, 2006). Further, 153 dancers may have a preferred limb for 'pushing off', jumping, or landing (Murphy, Connolly 154 & Beynnon. 2003). The asymmetric movement sequence of a dance routine highlights the 155 importance of bilateral symmetry in the lower limbs to decrease the risk of injuries attributed 156 to compromised movement technique and posture (Croisier, Ganteaume, Binet, Genty & 157 Ferret, 2008, Fousekis, Tsepis & Vagenas, 2010; Menzel, Chagas, Szmuchrowski, Araujo, de 158 Andrade & de Jesus-Moraleida, 2013). A comprehensive profile of ankle eversion and 159 inversion strength that considers bilateral asymmetry in addition to ipsilateral mode and speed-160 specific asymmetries, will inform clinical interpretation of the training needs required in this 161 cohort.

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163 2. Methods and Methods164

165 *2.1 Subjects*

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167 A cohort of 14 female amateur ballet dancers (age: 19.29 ± 1.59 years; height: 1.65 ± 0.05 168 metres; body mass: 61.00 ± 8.29 kilograms) were recruited to participate in the study. A random 169 stratified sampling method was deployed to recruit participants from exiting institutional 170 undergraduate dance populations, indicating that all participants were aged 18+. Stringent 171 inclusion criteria dictated that participants were not dancing for a professional organisation. 172 Further, all dancers had a minimum of 8 years dancing experienced and were required to be 173 attending ballet training for a minimum of three hours per week. Participants were unable to 174 participate in the study if they had sustained an injury in the 3 months prior to their testing 175 session or were categorised as having ankle instability based on completion of the Cumberland 176 Ankle Instability Tool (CAIT) questionnaire. The current study was approved by the institute's 177 departmental ethics committee, and, in accordance with the Declaration of Helsinki, all 178 participants obtained a study information sheet and provided written informed consent prior to 179 data collection.

- 180
- 181 *2.2 Procedures*

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183 All participants were required to attend the Musculoskeletal Laboratory for one experimental 184 testing session. Participants initially completed a standardized warm-up targeting ankle joint 185 mobilisation. Ballet-specific exercises - 10 x Plié, 10 x Relevé (heel raise) - were completed 186 in accordance with the constructs of a warm-up preceding a typical ballet class, and were 187 followed by 10 slow eversion and inversion repetitions for both limbs (seated with legs 188 outstretched) in reference to the subsequent isokinetic protocol. Five sub-maximal (50% effort) 189 familiarisation trials of concentric ankle eversion (CON_{EV}) and inversion CON_{INV}), and, 190 eccentric ankle inversion (ECC_{INV}) at all experimental testing velocities were completed as part 191 of the warm-up protocol. The familiarisation trials were completed with progressive increments in angular velocity through the sequence; $30^{\circ} \cdot s^{-1}$, $60^{\circ} \cdot s^{-1}$, $90^{\circ} \cdot s^{-1}$, and $120^{\circ} \cdot s^{-1}$ for both limbs. 192 Experimental trials were subsequently completed following a five-minute rest period, with five 193 194 maximal repetitions for each contraction mode and speed.

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196 2.2.1 Isokinetic strength assessment197

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

201 land on during a unilateral ballet-specific jump landing task, in accordance with previous 202 methods (Mertz and Docherty, 2012; Carcia, Cacolice & McGeary, 2019). For the purposes of 203 the current investigation, the preferred limb is classified as the dominant limb hereafter. Each 204 participant was positioned according to manufacturer's guidelines for ankle eversion/inversion 205 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 206 207 partially replicate the orientation of the foot when landing from a jump during a dance routine. 208 Each participants' foot was secured to the ankle eversion/inversion footplate attachment using 209 Velcro straps, whilst an additional dynamometer attachment positioned at the mid portion of 210 the posterior thigh provided support to the testing limb. To further stabilize and isolate the 211 ankle joint, Velcro straps were also applied across the chest, and the mid portion of the anterior 212 thigh of the uninvolved limb. From a neutral position (vertical alignment of the foot), and to 213 standardize the test protocol for all participants, ankle eversion and inversion motion limits 214 were set at 20° resulting in an overall 40° range of motion.

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216 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 217 angular velocities of $90^{\circ} \cdot s^{-1}$, $60^{\circ} \cdot s^{-1}$, $120^{\circ} \cdot s^{-1}$ and $30^{\circ} \cdot s^{-1}$ for both limbs, in accordance with 218 219 recommendations (Fish, Milligan & Killey, 2014). The non-linear order was chosen to 220 minimise any potential learning effect. The same procedure was then completed for the 221 eccentric ankle inversion trials. Concentric ankle eversion and inversion trials at each angular 222 velocity were interspersed with a one-minute rest period, whilst 10-minutes rest separated 223 ipsilateral concentric and eccentric trials to minimise the accumulation of fatigue (Yuksel, 224 Ozgurbuz, Ergun, Islegen, Taskiran, Deneral & Ertat, 2011). No performance feedback was 225 presented during any of the experimental trials. 226

227 2.3 Data Processing

228 229 Raw torque-angle time history data from each limb, contraction mode and angular velocity 230 were exported to Excel (Microsoft Corporation, Washington, USA) for further analysis. With 231 torque overshoot removed, the isokinetic phase of each repetition was determined, and the 232 repetition producing the highest torque was analysed. At each velocity and mode of contraction, 233 Peak Torque (PT), corresponding Angle of Peak Torque (APT), and Functional Range (FR -234 defined as the range over which 85% of peak torque is maintained) were established. Angle-235 Specific Torque (AST) data were calculated in 5° increments across the entire angular range 236 (40°) for all angular velocities and contraction modes. Corresponding Dynamic Control Ratios 237 (DCRs) were defined using PT (DCR_{PT}) and AST (DCR_{AST}) values.

- 238
- 239 2.4 Statistical Analysis
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241 Descriptive statistics are presented as mean \pm standard deviation (σ). The distribution of data 242 was quantified using histograms, Q-Q plots, skewness and kurtosis, and the Shapiro-Wilk 243 statistic. With the data normality assumption satisfied, linear mixed models were employed to 244 examine bilateral isokinetic strength differences in each outcome measure across all testing 245 velocities and contraction modes. Bonferroni-corrected post-hoc pairwise comparisons for 246 significant main effects and interactions were determined as required, and 95% confidence 247 intervals (CI) and Cohen's d effect sizes (small, 0.20-0.49; moderate, 0.50-0.79; large > 0.80) 248 were also presented. Alpha was determined a priori and deemed statistically significant at the 249 p < 0.05 level for all outcome measures. Statistical analyses were conducted using IBM SPSS 250 statistics V25.0 software (IBM, Armonk, New York, USA).

251 **3. Results**

252

253 *3.1 Peak torque* 254

255 Figure 1 summarises the influence of contraction mode and angular velocity on bilateral PT. 256 There was no significant main effect for limb (p = 0.35), nor any significant limb*contraction 257 mode (p = 0.72), limb*angular velocity (p = 0.96), or limb*contraction mode*angular velocity 258 (p = 1.00) interaction. Significant main effects for contraction mode (p = 0.001) and angular 259 velocity (p = 0.001) were identified, along with a significant contraction mode*angular velocity 260 interaction (p = 0.001). For instances where the main effect/interactions involving limb are not 261 significant, corresponding values for significant contraction mode, angular velocity and angle 262 main effects/interactions represent an average from the dominant and non-dominant limb and 263 this is consistent throughout. Figure 1 demonstrates that ECC_{INV} PT was significantly greater than CON_{EV} and CON_{INV} at $60^{\circ} \cdot s^{-1}$ (p = 0.001, d = 0.43-0.48), $90^{\circ} \cdot s^{-1}$ (p = 0.001, d = 0.67-264 0.73) and $120^{\circ} \cdot s^{-1}$ (p = 0.001, d = 0.73-0.77). 265 266

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

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271 *3.2 Angle of peak torque*272

273 Table 1 displays bilateral APT data for all contraction modes and velocities. No significant 274 main effect for limb (p = 0.82) was obtained, nor was there any significant limb*contraction 275 mode (p = 0.46), limb*angular velocity (p = 0.55), or limb*contraction mode*angular velocity 276 (p = 0.89) interaction. Analyses revealed a significant main effect for contraction mode (p = 0.89)277 0.001) with ECC_{INV} APT (27.10° \pm 7.16°; CI: 25.83-28.50) occurring significantly later in the 278 range of motion compared with CON_{EV} (18.45° ± 6.1°; CI: 17.20-19.70, p = 0.001, d = 0.55) 279 and CON_{INV} (16.62° \pm 6.46°; CI: 15.37-17.88, p = 0.001, d = 0.61) irrespective of angular 280 velocity. A significant main effect for angular velocity (p = 0.02) demonstrated that APT was achieved significantly earlier at $30^{\circ} \cdot s^{-1}$ (18.83° ± 9.03°, CI: 17.36-20.29) compared with $90^{\circ} \cdot s^{-1}$ 281 282 ¹ (22.17° \pm 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. 283 284

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

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288 289 *3.3 I*

3.3 Functional range 290 291 Figure 2 illustrates the influence of contraction mode angular velocity on bilateral FR There 292 was no significant main effect for limb (p = 0.10), and no significant limb*contraction mode 293 (p = 0.66), limb*angular velocity (p = 1.00), or limb*contraction mode*angular velocity (p = 1.00)294 (0.96) interaction. No significant main effect for contraction mode (p = 0.15) was found, 295 however a significant main effect for angular velocity (F = 17.37, p = 0.001) was revealed 296 irrespective of contraction mode. FR at $30^{\circ} \cdot s^{-1}$ (18.67° ± 5.95°; CI: 17.56-19.79) was significantly lower than at $60^{\circ} \cdot \text{s}^{-1}$ (21.06° ± 5.01°; CI: 19.99-22.22; p = 0.02, d = 0.20) but 297 significantly higher compared with $120^{\circ} \cdot s^{-1}$ (15.82° ± 6.27°; CI: 14.15-16.47; p = 0.001, d = 298 0.22). FR at $60^{\circ} \cdot s^{-1}$ was significantly greater than at $120^{\circ} \cdot s^{-1}$ (p = 0.001, d = 0.41), and at $90^{\circ} \cdot s^{-1}$ 299 $^{1}(19.38^{\circ} \pm 5.35^{\circ}; \text{CI: } 18.21\text{-}20.44)$ compared with $120^{\circ} \cdot \text{s}^{-1}$ (p = 0.001, d = 0.29). The significant 300

301 contraction mode*angular velocity interaction (p = 0.001) demonstrated that ECC_{INV} FR was 302 significantly greater at than CON_{EV} and CON_{INV} at $30^{\circ} \cdot s^{-1}$ (p = 0.001, d = 0.46-0.57), but significantly lower at $120^{\circ} \cdot \text{s}^{-1}$ (p = 0.001, d = 0.67-0.73). 303 304 305 306 307 ****INSERT FIGURE 2 HERE**** 308 309 310 3.4 Dynamic control ratios calculated from PT data. 311 312 DCR_{PT} values are presented in Table 2. There was no significant main effect for limb (p = 313 0.90), nor a significant limb*contraction mode (p = 0.15), limb*angular velocity (p = 0.75) 314 (0.05), or limb*contraction mode*angular velocity (p = 0.98) interaction. Significant main 315 effects for contraction mode (p = 0.001) and angular velocity (p = 0.001), and the 316 corresponding contraction mode*angular velocity interaction (p = 0.01) were highlighted. 317 There was no indication of any contraction mode*angular velocity interactions at $30^{\circ} \cdot s^{-1}$, however CON_{EV}:CON_{INV} dynamic control ratios were significantly greater than 318 CON_{EV}:ECC_{INV} and CON_{INV}:ECC_{INV} at $60^{\circ} \cdot s^{-1}$ (p = 0.01, d = 0.38-0.49), $90^{\circ} \cdot s^{-1}$ (p = 0.001, d 319 = 0.70-0.77) and $120^{\circ} \cdot s^{-1} p = 0.001$, d = 0.74-0.78) respectively. 320 321 322 323 ****INSERT TABLE 2 HERE**** 324 325 326 3.5 Angle-specific Torque 327 328 Figure 3 depicts the influence of contraction mode, angular velocity, and angle on bilateral 329 AST. There was no significant main effect for limb (p = 0.59), nor a significant interaction for 330 limb*contraction mode (p = 0.86), limb*angle (p = 1.00) limb*angular velocity (p = 0.95), 331 limb*contraction mode*angle (p = 1.00), limb*contraction mode*angular velocity (p = 0.68), 332 limb*angle*angular velocity (p = 1.00), or limb*contraction mode*angle*angular velocity (p333 = 1.00) interaction. Significant main effects for contraction mode (p = 0.001), angle (p = 0.001), 334 and angular velocity (p = 0.001), and, significant contraction mode*angle (p = 0.001), and 335 contraction mode*angular velocity (p = 0.001) were identified. Analyses revealed that ECC_{INV} 336 torque was significantly greater than the two concentric modes for angles $\geq 15^{\circ}$ during the 337 $30^{\circ} \cdot s^{-1}$, $60^{\circ} \cdot s^{-1}$ and $90^{\circ} \cdot s^{-1}$ trials, and for angles $\geq 25^{\circ}$ during $120^{\circ} \cdot s^{-1}$ (see figure 3). 338 339 340 ****INSERT FIGURE 3 HERE**** 341 342 343 3.6 Dynamic control ratios derived from AST data. 344 345 Table 3 summarises the effect of angle and angular velocity on the respective bilateral DCR_{AST}. 346 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 347 348 mode*angle (p = 1.00), limb*contraction mode*angular velocity (p = 0.47), 349 limb*angle*angular velocity (p = 1.00), or limb*contraction*mode*angle*angular velocity (p 350 = 1.00) interaction. However, significant main effects for contraction mode (p = 0.001), angle 351 (p = 0.01) and angular velocity (p = 0.001) were identified, along with a significant contraction 352 mode*angle (p = 0.001) and contraction mode*angular velocity (p = 0.02) interaction. At 353 angles $\geq 15^{\circ}$, CON_{EV}:CON_{INV} dynamic control ratios were significantly higher than 354 CON_{EV}:ECC_{INV} and CON_{INV}:ECC_{INV}. Moreover, CON_{EV}:CON_{INV} dynamic control ratios were 355 also significantly greater than the ECC_{INV}-inclusive ratios at all isokinetic speeds (see table 3). 356 There was no significant angle*angular velocity (p = 0.59) or contraction mode*angle*angular velocity (p = 0.97) interaction.

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

362 4. Discussion

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364 Strength deficits have been implicated as a modifiable risk factor for ankle injury, a prevalent 365 injury in ballet (Willems et al, 2005; Smith et al, 2015). Contrary to previous research, the 366 present study focused strength profiling on the ankle eversion/inversion mechanism that is 367 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 368 consideration of the aesthetic demand for movement symmetry within choreographed routines. 369 370 There was no evidence of bilateral asymmetry in any of the isokinetic ankle strength measures. 371 During a dance choreograph, a performer is presumed to execute technical intricacies using 372 each leg equally, and therefore, technique/rehearsal classes are assumed to facilitate bilateral 373 development (Farrar-Baker & Wilmerding, 2006). A key responsibility for the ankle joint is to 374 attenuate resultant mechanical loads following contact with the ground, to which strength plays 375 a pivotal role. With over half of jumps during a typical routine requiring a unilateral landing 376 component (Mertz & Docherty, 2012), symmetry between limbs is desirable to minimise a 377 greater loading and ensuing tendency to sustain injury in a particular side. The symmetry in 378 isokinetic strength in this population may be attributed to an early emphasis on bilateral limb 379 control in dance training, which may be crucial in developing equal bilateral strength, and 380 reducing ankle injury risk (Bronner & Ojofeitimi, 2006). Dance injury epidemiology literature 381 is not available to critically discuss this finding in relation to injury risk, however bilateral and 382 ipsilateral isokinetic strength discrepancies have been associated with an increased injury risk 383 (Croisier et al, 2008).

384

385 Potential strength imbalances were also considered in respect to contraction mode and 386 movement speed. The contraction mode*angular velocity interaction demonstrated that 387 ECC_{INV} strength was significantly greater than CON_{EV} and CON_{INV} at all but the slowest 388 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 389 390 reduces as a product of increasing angular velocity, whereas eccentric strength remains 391 relatively constant (Cress, Peters & Chandler, 1992). The higher values observed for ECC_{INV} 392 strength at the greater angular velocities – which arguably have better functional relevance with 393 regards to dance performance - may be crucial in preventing the inverted foot alignment 394 mechanism common to ankle sprain incidence (Kaminski, Buckley, Powers, Hubbard & Ortiz, 395 2003). 396

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,

401 consideration of the FR metric in isokinetic strength analyses may prove vital in identifying 402 markers for injury. At the slower velocities $(30^{\circ} \cdot s^{-1} \text{ and } 60^{\circ} \cdot s^{-1})$, ECC_{INV} FR was higher than both concentric modes. However, an inverse trend was established in the contraction 403 mode*angular velocity interaction at faster velocities ($90^{\circ} \cdot s^{-1}$ and $120^{\circ} \cdot s^{-1}$), whereby CON_{EV} 404 405 and CON_{INV} FR decreased marginally relative to the significant reductions demonstrated for 406 ECC_{INV}. In accordance with ankle injury aetiology (Skazalski et al, 2017) and the performance 407 characteristics of dance (Twitchett, Koutedakis & Wyon, 2009), the notable decline in ECC_{INV} 408 FR at higher velocities may have implications on injury susceptibility when executing dance-409 specific locomotion. Lower ECC_{INV} strength may compromise the ability to resist inversion 410 forces thereby proliferating injury risk (Fox et al, 2008). Rather than using PT – which provides 411 a single strength value for a pre-determined range of motion – in the pursuit of identifying 412 markers for injury, professionals with an injury reduction focus may benefit from the FR metric 413 during isokinetic strength testing. The significant reductions in ECC_{INV} FR at angular velocities 414 exceeding $60^{\circ} \cdot s^{-1}$ provides a focus for subsequent strength training interventions. Even if PT 415 and the maxima of strength curve is unchanged, a reduction in FR suggests a decrease in 416 strength away from the single joint angle defined as APT. Practically, a dancer would benefit 417 from high PT and FR since performance demands will move through an angular range at the 418 ankle. However, it should be acknowledged that a decrease in FR across all contraction modes 419 at higher velocities may be indicative of a limited isokinetic phase as the dynamometer crank 420 arm accelerates to higher speeds over a relatively small range of motion. Torque may indeed 421 be maintained at 85% of PT outside the isokinetic range, but the restricted focus on the 422 isokinetic data curtails the FR metric. The range of movement for ankle eversion and inversion 423 is smaller than knee flexion/extension for example (Eustace et al, 2017), and thus, FR values 424 appear to be joint specific and should be interpreted with this in mind. Moreover, direct 425 comparisons of FR between relevant studies may only be achievable when uniform 426 methodological designs are used.

427

428 Conventional DCRs are derived from PT values without any consideration of the angle at 429 which PT is achieved, and thus, limit an understanding of how strength changes as a function 430 of angle. Data from the current investigation demonstrated that Peak CON_{EV} and CON_{INV} 431 torque was achieved at ~18° (2° of inversion) and ~17° (3° of eversion), thereby representing 432 a relatively neutral foot alignment over the 40° range of motion. ECC_{INV} PT occurred 433 significantly later at $\sim 27^{\circ}$, representing a 7° position of inversion. Previous literature has failed 434 to quantify the angle of peak torque for ankle inversion/eversion isokinetic strength ratios, 435 preventing direct comparison. However, studies examining strength parameters at the knee 436 joint have demonstrated that APT varies between concentric and eccentric modes of 437 contraction and across a range of angular velocities (Cohen, Zhao, Okwera, Matthews & 438 Delextrat, 2015; Eustace et al, 2017). The evident inconsistencies for APT from the current 439 study and indeed other investigations, raises questions over the value of traditional PT-derived 440 strength ratios and supports the inclusion of AST assessed across a number of angular 441 velocities. The greater PT but smaller FR in ECC_{INV} at higher velocities has implications for 442 functional performance and the strategies deployed in training and/or rehabilitation. The 443 inverted configuration in ECC_{INV} – approximately 7° – compared with concentric modes may 444 serve as a protective mechanism against ankle injury during execution of dance-specific 445 movement, in which the foot is frequently loaded into inversion (O'Loughlin, Hodgkins & 446 Kennedy, 2008).

447

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

451 controls ratios were significantly higher for ECC_{INV} than CON_{EV} and CON_{INV}, with more 452 profound differences observed at the latter ranges of the movement, and with increasing 453 angular velocity. This finding may be attributed to both the force-velocity and force-angle 454 relationships between contraction modes. CON_{EV} and CON_{INV} strength portray a quadratic 455 trend, in which PT is achieved at approximately midpoint of the movement, whereas ECC_{INV} 456 PT is achieved towards end range. The use of angle-specific torque is sensitive to the changes 457 in strength at various positions within a movement. Resultant DCRs may be used in the 458 screening of performers towards injury reduction, and in the management of injury during 459 rehabilitation. For example, in the current study, whilst decreases in CON_{INV} strength near to 460 full ankle inversion were exacerbated as angular velocity increased, ECC_{INV} was relatively 461 consistent. ECC_{INV} dominance at the end ranges of movement and at higher velocities may 462 indeed reduce the likelihood of ankle injury when executing the jump-landing, cutting 463 manoeuvres of a dance routine.

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465 Caution ought to be taken when generalising these findings beyond the specific experimental 466 design employed. Isokinetic testing protocols have some inherent methodological constraints, 467 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 468 469 capabilities of the ankle when tested in this restricted state. Pilot testing highlighted that no 470 isokinetic phase was determined at angular velocities of $\geq 150^{\circ} \cdot s^{-1}$, and the range of motion is 471 prescribed using passive movement of the joint. Consequently, this passive manipulation of the 472 joint within an isokinetic testing paradigm may not reflect the physical capacity of the joint 473 during active movement. In the current investigation, limb dominance was determined using a 474 prospective classification based on preference to ballet-specific tasks. Carcia et al. (2019) 475 highlighted that limb dominance was task-specific, and thus, our approach is specific to the 476 participants and focus of our study. The use of alternative classifications of limb dominance, 477 including retrospective classification based on outcome measures, and the impact on 478 interpretation of the findings warrants future research. The present study focused on ankle 479 eversion/inversion strength given its mechanical associations with injury. However, a strength 480 profile of dancers may include plantar/dorsiflexion strength in light of kinematic analyses 481 highlighting ankle injuries to occur in neutral (Fong, Chan, Mok, Yung, & Chan, 2009) and 482 dorsi-flexed positions (Kristianslund, Bahr, & Krosshaug, 2011). Kinematic analyses of injury 483 incidence or dance-specific movements may inform bespoke isokinetic testing protocols but 484 must also account for physical limitations of the ankle during such assessments. Further 485 research is required in the associations between isokinetic metrics and injury incidence, which 486 may inform a threshold for the calculation of FR. Contemporary analysis metrics that delve 487 beyond the highest value of a strength curve are advocated. Data collection ought to utilise the 488 capacity of the isokinetic dynamometer to measure net joint torque at predetermined angles 489 and angular velocities to provide a screening battery of greatest functional relevance to the 490 sport. 491

- 492 **5.** Conclusions
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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} 501 strength is maintained over a range of angular velocities, compared with reductions in CON_{EV} 502 and CON_{INV} strength as movement speed increases. Specifically, dancers appear to be ECC_{INV} dominant at angular velocities of $60^{\circ} \cdot s^{-1}$ and beyond, and for all angular displacements 503 504 providing implications for functional performance and injury risk. Beyond the singular peak of the torque-angle curve, ECC_{INV} had greater FR at velocities $<90^{\circ} \cdot s^{-1}$ compared with the 505 concentric modes, which may indicate a protective mechanism for injury. The results and 506 507 methods highlighted within this study provide medical practitioners with the opportunity to 508 produce a comprehensive isokinetic strength profile of dancers. This information can be used 509 to help enhance understanding of injury occurrence, whilst producing more detailed information for a dancers return to performance. 510 511

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524 **Disclosure of interest**

526 The authors report no conflict of interest.

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- 635 Legend to Tables and Figures
- 636 637 *Tables*
- 638

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

641 **Table 2**. The influence of limb and angular velocity on selected Dynamic Control Ratios 642 calculated from PT. Values are mean $\pm \sigma$.

Table 3. The influence of limb, angle and angular velocity on the corresponding DCR_{AST} data. Values are mean $\pm \sigma$.

- 646 647 Figures
- 648

Figure 1. PT for each mode of contraction for the dominant (top) and non-dominant (bottom) limb. Values are mean $\pm \sigma$. * denotes a significant difference between the eccentric and concentric-inclusive contraction modes. 652

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

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

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