

1 **The Reliability of Physical Performance Testing within Elite Adolescent Pre-**  
2 **Professional Ballet Dancers**

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**The Reliability of Physical Performance Testing within Elite Adolescent Pre-  
Professional Ballet Dancers**

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71 **Abstract**

72 **Introduction:** Evaluating and training strength qualities is crucial for the physical  
73 development of ballet dancers. Whilst data is available as to the sensitivity of  
74 strength tests for detecting changes in athlete populations, between-session  
75 reliability for adolescent ballet dancers is yet to be determined. This study aimed to  
76 determine the between-session reliability of physical performance tests in elite  
77 adolescent ballet dancers. **Methods:** Depending on the test, a cohort of 25 to 54  
78 pre-professional ballet dancers (9 to 30 males, 14 to 29 females) participated in a  
79 series of six physical tests across 12 sessions. Each testing session involved  
80 performing one strength test, with retesting administered seven days later. The  
81 testing protocol included single-leg isometric squat, single-leg isometric  
82 plantarflexion, countermovement jump, standing single-leg countermovement jump,  
83 drop jump from 30 cm, and for males, seated overhead press to voluntary failure  
84 using 30 kg. Data was analysed using a pairs sample t-test, interclass correlation  
85 coefficients and measures of absolute reliability including values of minimal  
86 detectable change. **Results:** Pairs sample t-tests revealed no systematic bias was  
87 present between trial 1 and 2 for each test. Across all tests, interclass correlation  
88 coefficients ranged from *good* to *excellent* (0.89-0.98), and coefficients of variation  
89 were 2.6–6.5%. **Conclusion:** These results indicate strength testing can reliably be  
90 integrated into a comprehensive physical performance testing battery to identify  
91 changes associated with improved physical performance across the academic year  
92 for adolescent ballet dancers. Based on the minimum detectable change values,  
93 changes in jump performance across the range of tests employed in this study can  
94 likely be detected after relatively short training periods. However, maximal isometric  
95 strength tests such as the single-leg squat may require longer than six weeks to  
96 detect performance changes. The current study expands the testing options for ballet  
97 training centres and high-performance settings, ensuring confidence in accurately  
98 measuring physical changes.

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100 **Key words:** ballet, adolescent dancers, strength testing.

## 101 **Introduction**

102 The physical demands of elite ballet are considerable, with hours spent dedicated to  
103 classes, rehearsals and performances surpassing those observed in athletic  
104 populations.<sup>1</sup> Consequently, well-developed strength qualities are required to allow  
105 ballet dancers to maintain proper technical alignment, balance, and stability  
106 throughout a range of balletic movements, providing the foundation to height in  
107 jumps, extension in leg lifts, efficiency in overhead lifts, and stability in turns.<sup>2</sup>  
108 Furthermore, dancers' strength qualities underpin the ability to rapidly produce force,  
109 facilitating quick transitions between steps, accelerations, and leaps during allegro  
110 sequences performed in the studio and on stage.<sup>3</sup> Common methods used in various  
111 high performance athletic populations for evaluating lower and upper body strength  
112 qualities include testing maximal isometric force production,<sup>4</sup> muscular endurance<sup>5</sup>  
113 and jump performance.<sup>6</sup> The utilisation of such tests in ballet may offer valuable  
114 insights into dancers' physical capabilities and facilitate the design of tailored training  
115 programs, performance tracking, and injury risk management.<sup>7</sup>

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117 The reliability of performance tests in athletic populations have been documented.<sup>8,9</sup>  
118 For example, Carroll et al identified an intraclass correlation coefficient (ICC) of 0.92  
119 and a coefficient of variation (CV%) of 3.2% when examining performance during the  
120 countermovement jump test in Division-I college athletes.<sup>6</sup> Similarly, Blagrove et al  
121 and McGoldrick et al reported *good* to *excellent* reliability with high sensitivity for  
122 maximal isometric strength testing (ICC = 0.86-0.92, CV% = 4.4-8.4%) in adolescent  
123 distance runners and youth soccer players.<sup>10,4</sup> While this data may inform the  
124 interpretation for performance testing in youth athletes, ballet dancers exhibit distinct  
125 motor skills and physiological adaptations owing to the aesthetic nature of ballet,  
126 making ballet clear and distinct from more objective based high-performance  
127 activities.<sup>11,12,13</sup> This may result in divergent performance outcomes in strength tests  
128 due to set coordination patterns observed during activities like jump-landings. To  
129 date, reliability studies for strength testing in ballet have primarily focused on adult  
130 populations, with only 42% of participants in the Mattiussi et al study being elite  
131 ballet dancers, while the remaining participants were active individuals.<sup>14</sup> Kolokythas  
132 et al. tested elite adolescent ballet dancers but only evaluated one isometric strength  
133 test.<sup>15</sup> Consequently, the error associated with a range of physical performance tests  
134 for adolescent ballet dancers is unknown and needs further investigation. Reliability

135 data derived from a ballet population will better inform practitioners supporting the  
136 physical development of ballet dancers by helping to distinguish between potential  
137 'noise' and actual changes in test performance.

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139 Bilateral strength tests involving both legs have been the traditional approach for  
140 evaluating lower body strength in sports medicine.<sup>16</sup> However, determining  
141 performance using single-leg strength assessments may provide novel insights into  
142 force production capabilities.<sup>17</sup> For example, unilateral tests may offer further  
143 valuable insights into limb strength characteristics, particularly useful when  
144 establishing criteria for return-to-dance protocols following unilateral injuries or  
145 directing training emphasis in non-injured individuals with potential performance  
146 asymmetries.<sup>18</sup> Additionally, unilateral maximal isometric strength tests may provide  
147 a more accurate representation of an individual's maximal strength when compared  
148 to bilateral testing during standing tests, as the tolerance for spinal loading may no  
149 longer be the limiting factor for global force output.<sup>14</sup> Due to the scarcity of research  
150 employing unilateral strength testing among elite adolescent ballet dancers this  
151 necessitates further investigation to enhance practical insights.<sup>15,19</sup> When analysing  
152 the jumping demands of classical ballet, research has only recently quantified the  
153 loading associated with ballet training, highlighting that junior dancers perform a  
154 higher number of jumps than senior dancers, and males jump at a greater volume  
155 than females.<sup>20</sup> With jump counts during class ranging from 62 to 270—exceeding  
156 those reported in other jumping-based sports such as basketball and volleyball<sup>20</sup>—  
157 monitoring jumping performance is crucial not only for optimising performance but  
158 also for injury management. Given that jumping tasks account for over 50% of injury-  
159 related time loss in ballet companies, tracking jump performance can serve as both a  
160 performance metric and a key marker for return to full balletic training following  
161 injury.<sup>20</sup> Furthermore, from an artistic perspective, ballet company directors,  
162 choreographers, senior teachers, and experienced dancers regard power and  
163 jumping ability as essential attributes for success in professional ballet, underscoring  
164 the need for objective monitoring of jumping performance.<sup>3</sup>

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166 There is a need to consider gender-specific physical tests in ballet, given the  
167 differences in movement demands. For example, male dancers engage in extensive  
168 overhead lifting during performance and training<sup>2,21</sup> and, therefore, measures of

169 upper limb strength are important to inform programming for this population.<sup>5</sup>  
170 Additionally, male ballet dancers have an elevated risk of lower back injuries as a  
171 consequence of repetitively performing a high volume of lifts, necessitating an  
172 objective measure of upper body muscular endurance to inform attempts to mitigate  
173 the prevalent injury risk of the lower back, as highlighted by artistic and healthcare  
174 professionals in ballet settings.<sup>3</sup> As evidence for the accuracy of testing overhead  
175 lifting strength in male ballet dancers is currently limited, there is a need to  
176 investigate the reliability of testing overhead lifting capability.<sup>22</sup>

177

178 Muscular strength is crucial to performance in ballet<sup>2</sup>, suggested as a critical trait for  
179 a ballet dancer to possess by artistic staff when selecting prospective ballet  
180 dancers.<sup>3</sup> Therefore, determining the sensitivity of testing protocols will support  
181 practitioners in designing impactful training programs for dancers. However, currently  
182 there is a lack of evidence concerning their use in high-level dance environments,  
183 especially among adolescent dancers. Therefore, this study aims to determine the  
184 measurement error between sessions when testing single-leg isometric squat,  
185 standing single-leg isometric plantarflexion, countermovement jump, single-leg  
186 countermovement jump, drop jump, and for males, seated overhead press to  
187 voluntary failure adolescent elite ballet dancers.

188

## 189 **Methods**

### 190 *Study Design*

191 A between-session repeated measures design was used to determine the inter-  
192 session reliability of performance tests in pre-professional ballet dancers. Dancers  
193 reported to the Strength and Conditioning facility at the Royal Ballet School, with one  
194 test performed in each testing session. Re-testing was performed seven days later at  
195 the same time of day, before classes had started, to account for variations in  
196 circadian rhythm<sup>23</sup> and timetable demands. With six strength tests included in the  
197 physical performance testing battery, testing occurred over a 12-week period (Figure  
198 1). Performance tests included the single leg isometric squat (SL squat), standing  
199 single leg isometric plantarflexion (SL PF), seated overhead press repetitions to  
200 volitional fatigue with 30kg (OHP), countermovement jump (CMJ), single leg  
201 countermovement jump (SL CMJ), drop jump (DJ) tests. Prior to each testing  
202 session, a standardised warm up was performed.

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\*\*\*\*\*Insert Figure 1\*\*\*\*\*

*Participants*

*A priori* power analyses were performed using the calculation outlined by Walter et al. (1998)<sup>24</sup> indicating that a minimum of twenty-three participants were required to detect the minimal acceptable reliability of ICC values of 0.7. This calculation was based on a significance level ( $\alpha$ ) of 0.05 and a power ( $\beta$ ) of 80%, aiming to reach the expected reliability of ICC values greater than 0.9.<sup>6,14</sup> Due to the 12-week data collection period, not all participants completed both sessions for each test. Consequently, the participant characteristics vary for each test and are summarized in Table 1.

All participants were screened prior to testing to ensure physical health, with injured participants or recently injured participants (an injury was defined as a musculoskeletal condition that hindered normal training activities within the week leading up to data collection) excluded from data collection. Written consent was obtained from parents for all participants and ethical approval provided by the University of Essex Ethics Committee.

**Table 1.** Participant information for each test.

Test	<i>n</i>	<i>n</i> (male)	<i>n</i> (female)	Age (years)	Maturity Offset (years)	Height (cm)	Mass (kg)
Drop jump	44	25	19	17 ± 1	3.0 ± 1.3	171.8 ± 8.7	57.8 ± 8.8
Countermovement jump	59	30	29	17 ± 2	3.0 ± 1.8	174.4 ± 8.4	57.1 ± 8.9
Single-leg countermovement jump	54	28	26	17 ± 2	2.9 ± 1.8	171.4 ± 8.2	57.1 ± 8.5
Single-leg isometric squat	25	9	16	17 ± 1	3.5 ± 0.8	169.5 ± 6.1	54.8 ± 7.0
Single-leg isometric plantarflexion	26	12	14	17 ± 1	3.4 ± 0.9	171.6 ± 8.8	57.6 ± 8.6
Seated overhead press with 30kg	25	25	0	17 ± 1	2.4 ± 1.5	178.2 ± 6.0	65.4 ± 7.2

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239

240 *Procedures*

241 All participants were familiarised with the physical performance test before data  
242 collection having performed the tests in previous physical profiling sessions and  
243 given the option of a practice attempt before any data was collected. Coaching was  
244 provided where appropriate to ensure technical proficiency, data collection was  
245 initiated once dancers had verbalised they understood the protocol and were  
246 confident in performing the test. Testing sessions began with a 5-minute  
247 standardised, progressive warm-up involving 2 sets of 10 repetitions of bodyweight  
248 squat, hip hinge, calf raise, banded vertical pressing movements as well as 2 sets of  
249 10 repetitions of pogo jumps, 2 sets of 5 repetitions of single leg countermovement  
250 jumps and 2 sets of 5 repetitions of countermovement jump requiring submaximal  
251 efforts. All unilateral tests were collected on the left limb first, followed by the right  
252 limb to standardise the order of contractions. All isometric and jump tests were

253 conducted barefoot on a force platform (ForceDecks 4000, VALD Performance,  
254 Queensland, Australia) sampling at 1000 Hz. For all isometric strength tests, a  
255 custom isometric rig with 2.5 cm adjustable vertical spacing and a barbell (Original  
256 2028 Olympic Bar, Strength Shop, United Kingdom) were used, with a 5 cm thick  
257 foam pad (Olympic Neck Pad, Perform Better, United Kingdom) placed around the  
258 barbell for participant comfort. The vertical ground reaction force data acquired from  
259 each jump and the maximal isometric strength tests were analysed via the  
260 ForceDecks software (ForceDecks, VALD Performance, Queensland, Australia).  
261 Prior to the initial testing session for each test, bodyweight was collected during a  
262 static trial during which participants stood motionless on the force platform. Standing  
263 and seated height were collected one week before data collection using a medical  
264 grade measuring station (Seca 287 Wireless Ultrasonic Measuring Station,  
265 Hamburg, Germany). Maturity offset calculations were estimated using non-invasive  
266 anthropometric measures recording of each participant's gender, date of birth,  
267 standing stature, seated stature, and bodyweight.<sup>25</sup> Maturity offset can be defined as  
268 the as the time before or after PHV.<sup>26</sup> Data was collected by a trained nurse with  
269 extensive experience of collecting anthropometric data in adolescent populations.

270

### 271 *Drop Jump*

272 Utilising two force platforms, participants completed three DJs with approximately a  
273 1-minute rest interval between each trial. Participants stood on a 30 cm platform with  
274 their feet hip-width apart and hands placed on the hips. To initiate the DJ,  
275 participants stepped forward from the box before landing with both feet  
276 simultaneously on the force platforms. Upon landing, participants executed a  
277 maximal rebound vertical jump while maintaining hand contact with hips throughout.  
278 Participants were cued to "jump as high and as quickly as you can, spending as little  
279 time on the floor as possible by imagining the floor is hot like lava" before performing  
280 each test.<sup>27</sup> Participants had the option of a practice jump before data collection,  
281 followed by an additional 1-minute rest period. The recorded metrics included jump  
282 height in centimetres, calculated via the flight-time method (calculated via the  
283 ForceDecks software), ground contact time (the duration spent in contact with the  
284 ground between initial landing and take-off), and Reactive Strength Index (RSI),  
285 calculated using the equation of flight time divided by ground contact time. For data  
286 analysis, the mean value of the three attempts used.

287

### 288 *Countermovement Jump*

289 Participants performed three CMJs whilst standing on two force platforms with  
290 approximately 1-minute of rest between each attempt. Participants were instructed to  
291 stand on the force plate with their feet positioned between hip and shoulder width  
292 apart and their hands placed on their hips throughout the test. All attempts were  
293 performed to a self-selected depth and the participant was cued to “*shoot up like a*  
294 *rocket and jump as high as you can*” before each test.<sup>27</sup> Participants had the option  
295 of a practice jump before data collection, followed by an additional 1-minute rest  
296 period. Jump height was determined using the flight-time method with ForceDecks  
297 software (v2.0.7418, Vald Performance) and recorded in centimetres. The highest  
298 jump and the mean value of the three attempts used for data analysis. The flight-time  
299 method for calculating jump height was selected for its applicability in dance school  
300 environments, where basic equipment, limited budgets, and restricted access to  
301 advanced training tools are common.

302

### 303 *Single Leg Countermovement Jump*

304 Participants completed the SL CMJ on a single force platform, conducting three  
305 consecutive attempts with approximately 1-minute rest intervals between each  
306 attempt. Participants were instructed to descend to a depth of their choosing and  
307 were cued as above. To prevent additional leg swing from the non-jumping leg, its  
308 hip and knee were held at 90° flexion. Participants had the option of a practice jump  
309 on each leg before data collection, followed by an additional 1-minute rest period.  
310 Jump height was determined using the flight-time method with ForceDecks software  
311 and recorded in centimetres, with the highest and mean value of the three attempts  
312 used for data analysis.

313

### 314 *Single Leg Isometric Squat*

315 Participants stood in a partial squat position with a foam pad between their neck and  
316 the bar to ensure comfort and facilitate maximal force production, with the bar  
317 positioned to rest across the superior border of the scapular. The test foot was  
318 placed in the centre of a force platform with the hands gripping the bar using an  
319 overhand claw grip. A custom-built rig was employed to set the barbell at a height  
320 that permitted flexion of the knee and hip joints to 140°, where full extension for both

321 the knee and hip was 180°. <sup>14</sup> Knee angle was determined by aligning the fulcrum of  
322 the goniometer over the lateral epicondyle of the femur, while the stable arm was  
323 positioned in line with the lateral malleolus and the mobile arm aligned with the  
324 greater trochanter. For the hip angle, the fulcrum of the goniometer was placed over  
325 the greater trochanter, with the stable arm aligned with the femur and the mobile arm  
326 aligned with the glenohumeral joint. The contralateral limb was held in 90° of hip  
327 flexion to maintain a neutral hip positioning throughout the test. Participants were  
328 instructed “*you have 5 seconds to push maximally into the barbell as hard as you*  
329 *can, trying to bend the barbell*” before each trial. Each trial was initiated by the  
330 researcher instructing the participants to adopt the relevant position and then  
331 counting down “3, 2, 1, Push”, with trials lasting 5s in total. Participants performed  
332 three consecutive trials on each limb and were given approximately 10s rest  
333 between trials to reset prior to the next trial. While the optimal recovery duration  
334 between maximal isometric contractions remains debated<sup>29</sup>, we selected a relatively  
335 brief recovery period based on both established reliability from similar protocols<sup>14</sup>  
336 and time constraints of testing a large cohort.

337

### 338 *Single Leg Isometric Plantarflexion*

339 The SL PF test was selected to represent the strength qualities of all plantar  
340 flexors<sup>30</sup>, which are associated with jump performance.<sup>31</sup> Participants stood in the  
341 centre of the force platform with a foam pad between the neck and barbell positioned  
342 across the superior border of the scapular. The barbell was fixed inside a custom-  
343 built rig, with the barbell height set to account for individual variance in height. The  
344 ankle joint of the test foot was positioned at 130° of plantarflexion, measured using a  
345 goniometer with the fulcrum aligned to the lateral malleolus, the stable arm in line  
346 with the head of the fibula and the mobile arm in line with the base of the 5<sup>th</sup>  
347 metatarsal. Participants were cued to have a ‘soft knee’ on the test limb to prevent  
348 hyperextension at the knee joint and maintain a knee and hip flexion angle between  
349 170° and 180°. <sup>14</sup> The knee angle was determined by aligning the fulcrum of the  
350 goniometer over the lateral epicondyle of the femur, with the stabilisation arm  
351 positioned in line with the lateral malleolus and the mobile arm aligned with the  
352 greater trochanter. Hip position was measured by placing the goniometer's fulcrum  
353 over the greater trochanter, aligning the stabilisation arm with the lateral epicondyle  
354 of the femur and the mobile arm with the glenohumeral joint. The contralateral limb

355 was held at 90° of hip flexion to maintain a neutral hip positioning throughout test.  
356 Participants were instructed “*you have 5 seconds to push maximally into the barbell*  
357 *as hard as you can, trying to bend the barbell*” before each trial. Each trial was  
358 initiated by the researcher instructing the participants to adopt the relevant position,  
359 bracing, and then counting down “3, 2, 1, *Push*”. Trials lasted 5s in total. Participants  
360 performed three consecutive trials on each limb and were given approximately 10s  
361 rest between trials to reset before the next trial.

362

### 363 *Seated Overhead Press*

364 A 30kg Olympic barbell, measuring 10cm in circumference and 220cm in length, was  
365 securely positioned within a squat rack, placed in front of a conventional flat  
366 weightlifting bench with a height of 40cm. The participants assumed a sitting position  
367 on the bench with their feet flat on the floor and with an upright spinal posture.  
368 Participants were then instructed to execute the OHP with their hands positioned at  
369 shoulder-width apart in the front rack position, utilising an overhand claw grip.  
370 Participants were instructed to start each repetition with the barbell positioned just  
371 above the clavicles, then press it above the crown of the head while fully extending  
372 the elbows, before returning the barbell to below the chin to complete one full  
373 repetition. To warm-up, participants completed ten repetitions with a 20kg barbell  
374 followed by a 90s rest. For testing, participants pressed the barbell overhead, safely  
375 completing as many repetitions as possible with the loaded 30kg barbell. Throughout  
376 testing, an experienced safety spotter was present behind the participant to help and  
377 assist participants if they failed the test, or the barbell path deviated significantly  
378 backwards, putting the participant at risk, with no intervention before failure. Safety  
379 spotter arms were adjusted within the squat rack just below the bottom position of  
380 the OHP for each participant to ensure if test was failed, barbell would be safely  
381 collected within the squat rack. A second tester was present to perform a double  
382 count to confirm the final number of repetitions. The tester provided verbal feedback  
383 if the barbell did not reach the required depth below the chin or fully extend the  
384 elbows, allowing participants to self-correct their form; any repetitions failing to meet  
385 the criteria were discarded from the final test results. The test was stopped by the  
386 tester when the participant was unable to maintain correct technique with cueing or  
387 when no more repetitions could be completed. Lifting cadence was self-selected,  
388 with participants instructed that the barbell had to remain in constant motion

389 throughout the test duration. The OHP test was performed once, with the total  
390 number of successful repetitions completed used for data collection.

391

### 392 *Statistical Analysis*

393 For isometric strength testing, the mean vertical ground reaction force (vGRF) was  
394 extracted during static bodyweight trials. Peak vGRF was extracted during maximal  
395 isometric strength trials directly from the force platform software, with no filtering  
396 applied to vGRF data as per testing guidelines.<sup>32</sup> Measures of relative force being  
397 calculated as peak vGRF in Newtons being divided by body mass in kilograms.  
398 Descriptive statistics (mean  $\pm$  standard deviation) were calculated for all outcome  
399 variables associated with each test. For unilateral tests, variables were calculated for  
400 both limbs. The assumption of normality was confirmed using the Shapiro-Wilk test  
401 ( $\alpha = <0.05$ ). Initially, a paired samples t-test was used to calculate systematic bias  
402 between test 1 and test 2 from each performance test.<sup>33</sup> Relative reliability was  
403 assessed through the calculation of CV%  $((SD_{\text{pooled}} / \bar{X}_{1,2}) \times 100)$ <sup>33</sup> and using  
404 two-way mixed effects models for average measures of absolute agreement (ICC  
405 (2,k)) across outcome measures.<sup>34</sup> ICCs were reported with 95% confidence  
406 intervals and were interpreted as follows:  $<0.5$  *poor*,  $0.5-0.75$  *moderate*,  $0.75-0.9$   
407 *good*, and  $> 0.9$  *excellent*.<sup>34</sup> Absolute reliability was calculated using SEM  $(SD\sqrt{1-}$   
408  $ICC)$ <sup>33</sup> and MDC  $(SEM*1.96*\sqrt{2})$ .<sup>35</sup> Statistical tests were performed using JASP  
409 statistical software package (v0.17.1, University of Amsterdam, Netherlands).

410

### 411 **Results**

412 There was no systematic bias found between test 1 and 2 for any variable ( $p \geq 0.05$ ).  
413 Relative and absolute values of reliability for all measures are presented in Table 2.  
414 Relative reliability was *excellent* ( $ICC \geq 0.90$ ) for all variables except relative  
415 measures of SL squat strength on the left leg ( $ICC = 0.87$ ) and RSI scores derived  
416 from the DJ test ( $ICC = 0.89$ ), which demonstrated *good* relative reliability. Measures  
417 of absolute reliability are reported in Table 2 for each test measure, with CV%  
418 ranging from 2.6–5.9% for all variables.

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**Table 2.** Between-session reliability for all performance tests in elite adolescent pre-professional ballet dancers.

Test	Outcome measure	Test 1 Mean $\pm$ SD	Test 2 Mean $\pm$ SD	Change in mean	Between test p-values	ICC (95% CI)	CV%	SEM	MDC
Drop jump	RSI (s·s <sup>-1</sup> )	1.8 $\pm$ 0.5	1.7 $\pm$ 0.4	0.1	0.110	0.89 (0.80-0.94)	5.9	0.14	0.38
	Ground contact time (s)	0.29 $\pm$ 0.07	0.30 $\pm$ 0.07	0.01	0.133	0.92 (0.87-0.95)	5.0	0.02	0.05
	Jump height (cm)	30.7 $\pm$ 5.9	29.5 $\pm$ 5.6	1.2	0.181	0.93 (0.87-0.96)	3.4	1.5	4.1
Countermovement jump	Peak jump height (cm)	31.0 $\pm$ 7.6	31.4 $\pm$ 7.6	0.4	0.870	0.97 (0.95-0.98)	3.1	1.2	3.3
	Mean jump height (cm)	30.1 $\pm$ 7.3	30.3 $\pm$ 7.2	0.2	0.993	0.96 (0.94-0.98)	3.0	1.2	3.4
Single leg countermovement jump (right)	Peak jump height (cm)	14.3 $\pm$ 4.0	14.0 $\pm$ 4.1	0.3	0.244	0.95 (0.92-0.97)	5.0	0.9	2.5
	Mean jump height (cm)	13.4 $\pm$ 3.8	13.3 $\pm$ 3.9	0.1	0.670	0.96 (0.94-0.98)	4.7	0.7	2.1
Single leg countermovement jump (left)	Peak jump height (cm)	14.8 $\pm$ 4.3	14.6 $\pm$ 4.2	0.2	0.578	0.96 (0.93-0.97)	4.1	0.8	2.3
	Mean jump height (cm)	13.8 $\pm$ 3.9	13.7 $\pm$ 4.1	0.1	0.655	0.98 (0.96-0.99)	3.8	0.6	1.7
Single-leg isometric squat (right)	Absolute vGRF (N)	1663.8 $\pm$ 403.1	1665.0 $\pm$ 417.0	1.2	0.392	0.93 (0.88-0.96)	4.4	103	285
	Relative vGRF (N·kg <sup>-1</sup> )	29.7 $\pm$ 5.8	29.7 $\pm$ 5.4	0.0	0.343	0.90 (0.82-0.94)	4.5	1.8	5.0
Single-leg isometric squat (left)	Absolute vGRF (N)	1604.9 $\pm$ 370.5	1569.9 $\pm$ 391.4	35	0.980	0.91 (0.86-0.95)	4.8	119	330
	Relative vGRF (N·kg <sup>-1</sup> )	28.0 $\pm$ 5.9	28.7 $\pm$ 5.3	0.7	0.990	0.87 (0.79-0.93)	4.9	2.0	5.5
Single-leg isometric plantarflexion (right)	Absolute vGRF (N)	1561.1 $\pm$ 340.2	1560.1 $\pm$ 415.7	0.1	0.966	0.97 (0.96-0.98)	2.9	61	168
	Relative vGRF (N·kg <sup>-1</sup> )	26.3 $\pm$ 3.9	26.3 $\pm$ 5.1	0.0	0.950	0.96 (0.93-0.97)	3.0	1.0	2.7
Single-leg isometric plantarflexion (left)	Absolute vGRF (N)	1601.3 $\pm$ 372.0	1616.7 $\pm$ 379.2	15.4	0.500	0.98 (0.96-0.99)	2.6	56	156
	Relative vGRF (N·kg <sup>-1</sup> )	26.9 $\pm$ 4.0	27.2 $\pm$ 4.5	0.3	0.411	0.94 (0.90-0.97)	2.7	1.0	2.8
Seated overhead press (30kg)	Number of repetitions performed	19 $\pm$ 8	20 $\pm$ 8	1	0.331	0.98 (0.96-0.99)	6.5	1	3

vGRF = Vertical ground reaction force; ICC = Intraclass correlation coefficient; SEM = Standard error of measurement; MDC = Minimal detectable change

## 424 Discussion

425 This study aimed to establish the between-session reliability for a testing battery  
426 examining physical performance in elite adolescent ballet dancers. The results show  
427 that measures representing performance during lower extremity maximal isometric  
428 force production, jumping and upper extremity strength endurance tests demonstrate  
429 *good to excellent* relative reliability and CV% ranging from 2.6-5.9%. Hence, strength  
430 tests can be reliably incorporated into a comprehensive performance testing battery  
431 to detect performance changes typically associated with strength gains observed  
432 following a training intervention in this population. Within the between-session  
433 design, no systematic bias was observed between tests, indicating the absence of  
434 learning effects, participant bias, or acute adaptations.<sup>33</sup> These results imply that the  
435 procedures employed in this study are suitable for minimising the effects of  
436 systematic error.

437

438 This investigation assessed the reliability of the DJ test, *good* reliability was  
439 observed for RSI (ICC = 0.89, CV% = 5.9%), while ground contact time (ICC = 0.92,  
440 CV% = 5.0%), and jump height (ICC = 0.93, CV% = 3.4%) demonstrated *excellent*  
441 reliability. When contrasted with other studies exploring the reliability of DJ  
442 performance from a 30 cm drop height, Xu et al. (2023) reported comparable  
443 findings, with *excellent* between-session reliability for jump height (ICC = 0.95, CV =  
444 5.4%), ground contact time (ICC = 0.97, CV = 5.9%), and RSI (ICC = 0.95, CV =  
445 7.7%).<sup>36</sup> This result was unexpected, as we anticipated greater variation in drop  
446 jump performance among dancers. This expectation was based on the unique  
447 landing strategies dancers employ in ballet to meet artistic demands, particularly the  
448 pronounced ankle plantarflexion used during initial ground contact<sup>37</sup>, potentially  
449 affecting force production relying on a fast stretch-shortening cycle.<sup>38</sup> Additionally, as  
450 the DJ test is not a widely used test within ballet, the novel exposure to this task  
451 combined with a unique landing strategy may increase between-session variance in  
452 jump performance.<sup>39</sup> This may be further evident if collecting data via equipment  
453 utilising optical sensor technology when comparing to force plate data, as landing  
454 and take-off technique may affect comparisons in jump height.<sup>40</sup> However, the  
455 results of this study indicate that practitioners working with dancers should expect  
456 similar variance in drop jump test performance as seen in other populations. From a  
457 practical perspective, MDC values from this study appear sensitive enough to

458 identify performance improvements after a 12-week plyometric training program  
459 which showcased a 10cm improvement in DJ height following intervention of  
460 plyometric training on one side of the body and resistance training on the other side,  
461 showing a 1.3cm height improvement.<sup>41</sup> However, it should be mentioned this  
462 population differed to ours with utilising only males of a mean age of  $22 \pm 2$  with no  
463 experience of regular resistance training. These results suggest this test provides  
464 value for assessing improvements in fast stretch-shortening cycle performance  
465 among ballet dancers. Moreover, as highlighted by Beattie and Flanagan, if the  
466 scores from athletes or dancers exceed that of the CV% calculated then the  
467 practitioner can be confident the change in DJ RSI is 'worthwhile' and is a result of a  
468 biological change in the athletes training status.<sup>42</sup>

469

470 For measures of jump height from the CMJ and SL CMJ, our findings suggest the  
471 between-session reliability was *excellent* (ICC = 0.95-0.98), with CV% ranging 3.0-  
472 5.0%. These findings are consistent with the literature<sup>43,44,45</sup>, demonstrating the  
473 appropriateness of these tests for measuring strength performance utilising a slow  
474 stretch-shortening cycle in adolescent populations. This investigation is the first to  
475 determine these values in elite pre-professional ballet dancers. Notably, eight-week  
476 training interventions for both male<sup>46</sup> and female<sup>47</sup> adolescent athletes have  
477 demonstrated improvements in CMJ height that surpass the MDCs observed in this  
478 study. The measures of countermovement jump height appear to have sufficient  
479 reliability to detect changes after a relatively modest period of training (e.g., 1-2  
480 training blocks). Although not statistically tested, our observation of the data aligned  
481 with Moir et al, suggesting no notable difference in reliability when using either the  
482 highest jump of three attempts or the mean of three attempts to calculate jump  
483 performance.<sup>48</sup> When deciding between using the highest jump or the mean of three  
484 attempts, practitioners should prioritise their philosophical approach rather than  
485 focusing exclusively on the accuracy of outcome measures. For instance, coaches  
486 evaluating a dancer's maximum force production capacity during a slow stretch-  
487 shortening cycle activity might select to analyse the highest jump as representative  
488 of CMJ performance.

489

490 For measures of maximal isometric force tests using the SL squat and SL PF test,  
491 these findings revealed *good* to *excellent* agreement (ICC = 0.87-0.98), with CV%  $\leq$

492 4.8% for absolute vGRF and  $\leq 4.9\%$  for relative vGRF on both left and right limbs.  
493 This data is comparable to investigations measuring isometric strength qualities in an  
494 athletic population<sup>49</sup> and similar to that reported by Mattiussi et al, where ICC values  
495 ranged from 0.97 to 1.00, and CV% ranged from 2.0% to 5.9%.<sup>14</sup> However, it is  
496 important to acknowledge that, as the Brady et al. (2020) paper reviewed multiple  
497 studies, the participants varied in athletic ability, age, strength training experience,  
498 and joint angles compared to the dancer population in this study.<sup>49</sup> Furthermore,  
499 Mattiussi et al included both dancers and physically active males and females, with  
500 mean ages of  $27.9 \pm 6.3$  and  $29.3 \pm 8.6$ , respectively.<sup>14</sup> This differs significantly from  
501 our study, which focused solely on dancers and involved a different age  
502 demographic. Notably, the MDC values in this study were higher than those reported  
503 by Kolokythas et al for the isometric mid-thigh pull (285–330N vs. 134N), suggesting  
504 that the isometric mid-thigh pull may offer greater sensitivity than the SL squat test.<sup>15</sup>  
505 Based on the MDC values presented in this investigation, maximal isometric force  
506 tests may not possess sufficient sensitivity to detect changes in strength following a  
507 relatively short strength training intervention. For example, Lynch et al found that  
508 recreational athletes following a 6-week bilateral or unilateral strength training  
509 programme, improved their bilateral and unilateral squat performance by 243N and  
510 153N respectively.<sup>50</sup> These values fall below the MDC values observed in the  
511 present investigation's unilateral variant, representing 95% confidence intervals.  
512 Consequently, the isometric strength tests in the present study likely lack sufficient  
513 reliability to confidently detect performance changes after a single block (e.g., 4-6  
514 weeks) of resistance training in adolescent ballet dancers. Therefore, detecting  
515 changes in maximal isometric force production during the SL squat may require  
516 extended training periods.

517

518 When examining the seated OHP test, this investigation revealed *excellent* between-  
519 session reliability for male dancers (ICC = 0.98, CV = 6.5%). To the authors'  
520 knowledge, no published research currently exists determining the reliability for the  
521 seated OHP to failure in healthy populations, with available research focusing  
522 predominantly on one repetition max testing in well trained men<sup>51</sup> or horizontal  
523 pressing movements.<sup>52</sup> However, assessment for strength endurance in the upper  
524 extremity demonstrate similar acceptable reliability. For example, Henriques-Neto  
525 and colleagues found the push-up test for maximum repetitions in young athletes

526 between 9-18 years of age demonstrated *good* reliability (ICC = 0.86).<sup>53</sup> The OHP  
527 test was selected for this investigation due to its mechanical resemblance to lifts  
528 performed by male ballet dancers, involving significant shoulder elevation<sup>54</sup> that likely  
529 exceeds values observed during horizontal pressing activities.<sup>55</sup> Another  
530 consideration for the OHP test was that dancers were not restricted to performing  
531 lifts at a specific cadence, unlike in other tests of strength endurance.<sup>56</sup> This is an  
532 important consideration for practitioners using the OHP test, as research indicates  
533 that allowing individuals to choose their lifting tempo significantly increases the  
534 number of repetitions completed, average work performed, and average power  
535 displayed, compared to standardised cadences such as 2-second ascent with a 2-  
536 second descent, and a 2-second ascent with a 4-second descent.<sup>57</sup> In this study,  
537 lifting cadence was left uncontrolled to avoid the extended time needed for  
538 familiarisation and the difficulties in monitoring lifting speed, particularly when testing  
539 large cohorts with limited time available. Importantly, the data from this study show  
540 that the OHP test has sufficient sensitivity to detect potential in performance  
541 following an intervention.

542

## 543 **Conclusion**

544 The current study aimed to establish the between-session reliability of a testing  
545 battery assessing physical performance in elite adolescent ballet dancers. The data  
546 demonstrated *good* to *excellent* relative reliability for outcome measures related to  
547 jumping, lower extremity maximal isometric force production and upper extremity  
548 strength endurance tests. These results indicate that strength and power tests can  
549 be reliably integrated into a comprehensive performance testing battery to detect  
550 performance changes associated with strength gains following training interventions  
551 in this population. This expands testing options for adolescent ballet training centres  
552 and high-performance settings, ensuring confidence in their accuracy for measuring  
553 physical changes. The study suggests that these tests can effectively establish  
554 baseline performance data for power, strength and strength endurance, enabling  
555 practitioners to monitor performance changes accurately following physical  
556 interventions.

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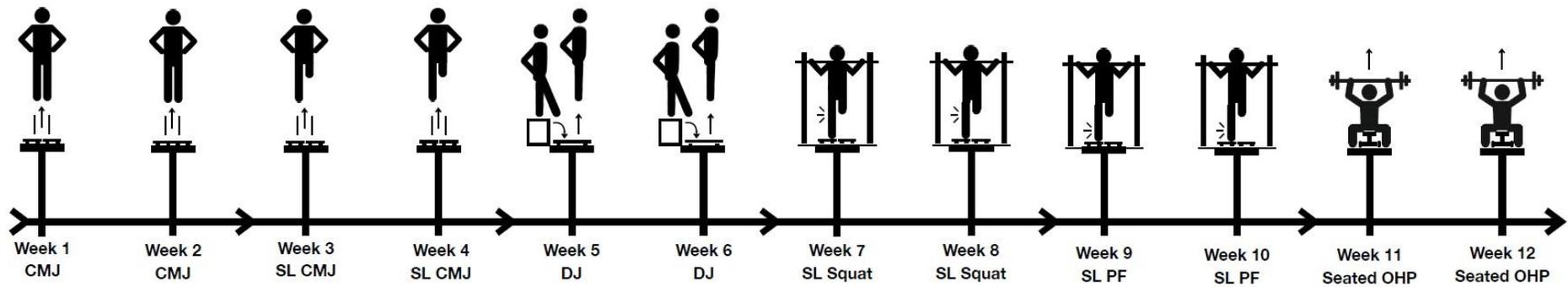
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759 **List of Legends**

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761 **Figure 1.** Timeline for data collection across the 12-week testing period.



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