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# Within- and between-day loading response to ballet choreography

Philip Nagy[a], Chris Brogden[a], Gabrielle Orr[b] and Matt Greig[a]

[a]Sports Injuries Research Group, Department of Sport & Physical Activity, Edge Hill University, Ormskirk, Lancashire, UK.; [b]Department of Creative Arts, Edge Hill University, Ormskirk, Lancashire, UK.

**ABSTRACT**

Overuse pathologies are prevalent in ballet injury. Ten amateur ballet dancers (age: 23.20 ± 3.08 years) completed a progressive 5-stage choreographed routine on two consecutive days. Tri-axial accelerometers positioned at C7 and the dominant and non-dominant lower-limb were used to calculate accumulated PlayerLoad™ ($PL_{TOTAL}$) and uni-axial contributions of the anterior-posterior ($PL_{AP}$), medial-lateral ($PL_{ML}$), and vertical ($PL_V$) planes. $PL_{TOTAL}$ increased significantly ($p = 0.001$) as a function of exercise duration within-trial, however there was no significant change between trials ($p = 0.18$). $PL_{TOTAL}$ at C7 was significantly ($p = 0.001$) lower than both lower-limbs, with no bilateral asymmetry evident ($p = 0.97$). Planar contributions to $PL_{TOTAL}$ were significantly greater in $PL_V$ than $PL_{AP}$ and $PL_{ML}$ ($p = 0.001$). PlayerLoad™ demonstrated within-trial sensitivity to the progressive routine, however no residual fatigue effect was observed between trials. The results of this study suggest that accelerometers have efficacy in athlete monitoring and injury screening protocols, however unit placement should be considered for practical interpretation.

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Accelerometry; ballet; fatigue; load; overuse

## Introduction

Overuse injury diagnoses represent approximately 70% of all cases in amateur ballet dancers (Smith et al., 2015). Overuse injuries are multifactorial, but may be attributed to poor training periodization, acute and chronic excessive loading, and insufficient recovery (Aicale et al., 2018; Cheron et al., 2016). Each ballet training/performance exposure presents a risk of injury (Bowen et al., 2019), whilst the demanding training regimens initiated at an early age require many hours of training and competition (Murgia, 2013). Research has demonstrated that 33% of dancers take less than 20 minutes rest during a typical workday (Twitchett et al., 2010), potentially influencing the greater incidence of injury observed in the latter stages of a performance and towards the end of a season (Liederbach et al., 2008). Strategies to reduce the impact of overuse injury include restrictions on training and competition workloads in other sports (Schaefer et al., 2018), however, there is currently no governing body legislation relating to exposure in ballet. Nevertheless, dancers must avoid the perilous combination of excessive workloads and inadequate recovery to mitigate

**CONTACT** Philip Nagy philipnagy@hotmail.com School of Science, Technology and Health, York St John University, York, United Kingdom. Y031 7EX.

performance decrements and an increased injury risk (Meeusen et al., 2013; Schwellnus et al., 2016; Soligard et al., 2016). To that end, efforts towards developing a greater understanding within a ballet context are worthwhile.

Previous biomechanical investigations in ballet have typically been confined to a laboratory environment with performance tasks lacking validity regarding the physical demands of ballet (Orishimo et al., 2009; Liederbach et al., 2014; Turner et al., 2018). Greater ecological validity in the research paradigm is afforded by the use of accelerometry (Boyd et al., 2011), and the use of dance-specific exercise protocols such as the Dance Aerobic Fitness Test (DAFT) (Wyon et al., 2003). Accelerometry facilitates a tri-axial evaluation of mechanical loading, providing a means to identify sub-optimal training loads which have been associated with an increased risk of injury (Bowen et al., 2017; Colby et al., 2014). However, the validity of the conventional mid-scapula placement of the accelerometer to quantify whole-body load has been questioned in contemporary research, which has advocated anatomical placement informed by injury epidemiology (Brogden et al., 2018; Greig & Nagy, 2017). In ballet, the lower-limb is the most common site of injury (Smith et al., 2015), and research has demonstrated that loading during the DAFT protocol was greater in the dominant lower-limb compared with mid-scapula (Brogden et al., 2018). Consequently, the aim of the current study was to develop an experimental paradigm to reflect the physical demands and training regimens typical of ballet. Specifically, the study aimed to quantify both the within– and between-performance loading response to a choreographed ballet routine comprising multiple stages of progressive intensity. The asymmetric movement profile inherent to ballet is reflected in training strategies targeting equal input from both lower-limbs, but also provides a rationale for a bilateral evaluation in research. Hence, the current study also aimed to quantify the loading response at both the dominant and non-dominant lower-limb.

## Materials and methods

### *Participants*

Ten female ballet dancers (age: 23.20 ± 3.08 years; height: 164.45 ± 5.46 cm; body mass: 65.31 ± 8.47 kg) volunteered and provided written informed consent to take part in the study, in respect of the Declaration of Helsinki. Inclusion criteria dictated that participants were free from lower-limb musculoskeletal injury in the 6 months prior to testing, whilst attending ballet training for a minimum of 3 hours per week. Participants with neural, visual and/or vestibular disorders were prohibited from participating in the study. All participants undertook extensive pre-exercise health screening involving completion of a thorough medical questionnaire. Both heart rate and blood pressure were measured at rest (Omron MX3 Plus, Omron Healthcare, Kyoto, Japan), with values of <90 bpm and 140/90 sys/dia mmHg necessary.

### *Procedures*

All participants attended the same dance studio on three separate occasions to complete a familiarization trial and two experimental trials. The familiarization trial required the dancers to complete each stage of a ballet-specific choreographed routine (See Table 1), which was taught and delivered by a qualified dance instructor. Following a 72-hour rest period, the same ballet-specific routine was completed for the two experimental trials, separated by 24 hours. All participants were instructed to wear clothing and footwear similar to that worn during training/performance, whilst being advised to avoid exercise and recovery strategies between testing sessions. A typical ballet class warm-up consisting of barre and centre work along with self-selected dynamic stretching preceded the experimental trials. All testing sessions commenced at 10am, thereby negating circadian rhythm variations and simulating an authentic training environment.

### Ballet-specific choreographed routine

The experimental dance piece was choreographed in accordance with the principles of the DAFT protocol (Wyon et al., 2003). The routine was designed to include the specific, multi-planar movements inherent to ballet performance, and is described in Table 1.

Each stage lasted 4 minutes, and the within-stage movement sequences were completed for the left and right limb. A one-minute rest period interspersed each stage, whilst the overall duration of the choreographed routine was 20 minutes. The technical components and tempo of exercise were carefully controlled for in each stage and chosen to demonstrate progressive intensity. The graded increment in intensity was achieved via manipulation of the discrete ballet manoeuvres, synonymous with petit and grand allegro.

## Data processing

The tri-axial accelerometer of a GPS device (Optimeye S5, Catapult Innovations, Melbourne, Australia) was used to quantify mechanical load responses to the ballet-

**Table 1.** Technique descriptors and corresponding tempos for each stage of the ballet-specific choreograph and the DAFT protocol (Wyon et al., 2003).

| | Stage | Tempo ($b{\cdot}min^{-1}$) | Movement Description |
|---|---|---|---|
| Current Study | 1 | 70 | Plié, Relevé, Sauté, Changement, Entrechat quatre, Echappé, Royale/changement battu. |
| | 2 | 85 | Glissade, Echappé, Petit Jeté, Petit Temps levé, Temps de cuisse. |
| | 3 | 85 | Failli, Assemble (de coté devant), Pas de chat, Balloté, Balloné, Sissonne (double, ouvert, fermeé). |
| | 4 | 105 | Grand Temps levé, Cabriole derriere, Pirouette (en dehors), Grand pas de chat, Grand assemblé. |
| | 5 | 105 | Grand Jeté, Posé (Arrabesque/attitude derriere), Grand Assemblé en tournant (en l'air), Temps levé, Developpé Temps levé, Grand Sissonne ouvert turning, Bournonville Jeté, Coupé chassé en tournant, Grand Jeté en tournant, Posé pirouette. |
| DAFT | 1 | 68 | 5 steps, lunge and recover. 4 × 2 pliés with 90° turn between each set. |
| | 2 | 78 | 5 steps, lunge and recover. 3 spring hops in a circle. 4 x hop plié with 90° turn between each set, arms moving between 1st and 2nd position. |
| | 3 | 78 | 5 steps, lunge and recover. 3 spring hops in a circle with arm movements. 4 x hop plié with 90° turn between each set, arms moving between 1st and 2nd position. |
| | 4 | 94 | 5 steps, lunge and recover. 3 spring hops in a circle with arm movements. 4 x hop, hop with 90° turn between each set, arms moving between 1st and 2nd position. |
| | 5 | 108 | 5 springs, lunge and recover. 3 spring hops in a circle with arm movements. 4 x hop, hop with 90° turn between each set, arms moving between 1st and 2nd position. |

$b{\cdot}min^{-1}$, beats per minute; DAFT, Dance Aerobic Fitness Test.

specific choreography, with data sampling at 100 Hz. A unit was housed in a manufacturer-provided neoprene vest and positioned at mid-scapula (approximating the $7^{th}$ cervical vertebrae (C7)), with an additional unit placed on the distal aspect of the dominant (DL) and non-dominant (NDL) leg. Underwrap tape (Mueller Sports Medicine Incorporated, Wisconsin, USA) was used to secure the GPS device at a location 50% of the distance between the calcaneus and the posterior mid-point of the femoral epicondyles (approximately mid-gastrocnemius), in accordance with previously established methods (Brogden et al., 2018). Accumulated PlayerLoad™ ($PL_{TOTAL}$), defined as the sum of the PlayerLoad™ vector magnitudes in each movement plane (medial-lateral ($PL_{ML}$), anterior-posterior ($PL_{AP}$), and vertical ($PL_V$)) was calculated at C7 and the bilateral lower-limb. Uni-axial planar contributions ($PL_{ML\%}$, $PL_{AP\%}$, $PL_{V\%}$) to total load were also quantified. PlayerLoad™ and its planar contributors ($PL_{ML}$, $PL_{AP}$, $PL_V$) demonstrate convergent validity and moderate to high (ICC: 0.80–0.97; CV 4.2–14.8%) test-retest reliability (Barrett et al., 2014).

To quantify internal measures of training load, peak heart rate (HR) and rating of perceived exertion (RPE) were recorded after each stage of the choreographed routine using HR monitors (HRM1G & Forerunner 15, Garmin, Kansas, USA) and Borg's 6-20 point scale (Borg, 1982), respectively.

### *Statistical analysis*

All data were analysed using a statistical software package (SPSS IBM Statistics V25.0, IBM, Armonk, New York, USA) with descriptive statistics presented as mean ± standard deviation. Assumptions of normality were satisfied via histograms and the Shapiro-Wilk statistic. Repeated measures ANOVAs were used to quantify within-trial and between-trial differences in each dependent variable during the ballet-specific Choreographed routine. Where appropriate, post-hoc comparisons using a Bonferroni correction factor were conducted to identify where differences occurred. 95% Confidence Intervals (CIs) are presented for significant findings, along with Cohen's *d* (Cohen, 1988) effect sizes (small, 0.20–0.49; moderate, 0.50–-0.79; large >0.80). Differences were deemed statistically significant at the $p < 0.05$ level.

## Results

### *Choreographed routine load responses – $PL_{TOTAL}$*

Data on within- and between-day changes in $PL_{TOTAL}$ across the ballet-specific choreographed routine is displayed in Figure 1. A significant main effect was identified for stage ($p < 0.01$), with $PL_{TOTAL}$ increasing as a function of performance duration and intensity. There was no significant difference in load responses between day 1 (118.44 ± 18.26 au; CI: 108.66–128.22 au) and day 2 (109.50 ± 15.78 au; CI: 109.50–117.08 au, $p = 0.18$), and no significant day *x* stage ($p = 0.44$) interaction.

A significant main effect for unit position ($p < 0.01$) was identified, along with the stage *x* unit position interaction ($p < 0.01$). Post hoc analyses revealed that $PL_{TOTAL}$ was lower at C7 compared with the lower-limbs ($d = 0.94$–$0.98$), with the differences becoming more pronounced during the later stages (3–5) of the routine. There was no significant

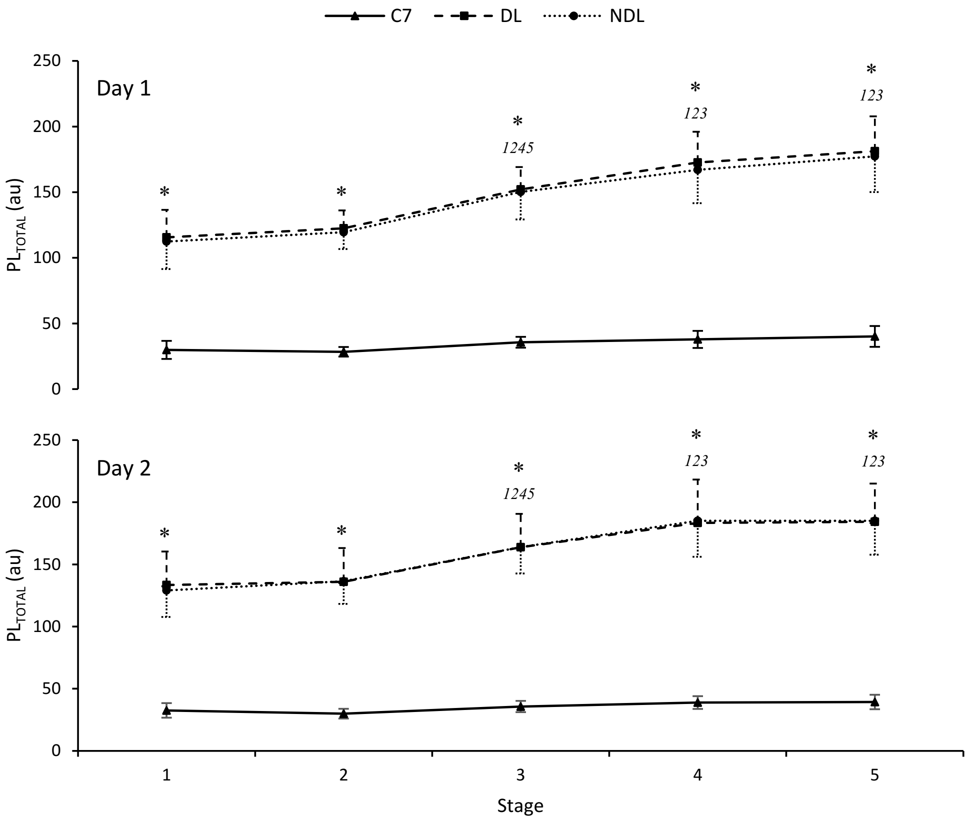


**Figure 1.** Within– and between-day $PL_{TOTAL}$ responses to the choreographed routine at C7 and in the dominant (DL) and non-dominant (NDL) limb. * Denotes a significant main effect for unit position.[12345] signify the pairwise comparisons from stage 1 ([1]) to stage 5 ([5]).

difference between the lower-limbs ($p = 0.97$), and no significant day *x* unit position ($p = 0.45$), or day *x* stage *x* unit position ($p = 0.90$) interaction.

## *Load responses – relative uni-axial contributions*

Uni-axial load contributions to $PL_{TOTAL}$ are displayed in Table 2. There was no significant main effect for stage ($p = 0.66$), day ($p = 0.53$), or unit position ($p = 0.73$) in any plane. However, there was a significant main effect identified for uni-axial contribution ($p < 0.01$), with PLv (41.07 ± 1.92%; CI: 40.65–41.49) representing a significantly larger contribution to $PL_{TOTAL}$ compared with $PL_{AP}$ (27.40 ± 1.45%; CI: 27.12–27.67, $p = 0.001$, $d = 0.97$) and $PL_{ML}$ (31.54 ± 1.52%, CI: 31.10–31.97; p 0.001, $d = 0.94$). $PL_{AP}$ was significantly lower than $PL_{ML}$ ($p < 0.01$, $d = 0.81$).

Post hoc analysis of a significant day *x* uni-axial contribution interaction ($p < 0.01$) revealed that $PL_{ML}$ (31.21 ± 1.40%; CI: 30.83–31.59) on day one was significantly lower than on day two (31.86 ± 1.64%; CI: 31.23–32.50, $p = 0.03$, $d = 0.21$), whilst $PL_V$ was significantly higher on day one (41.60 ± 1.83%; CI: 41.04–42.16) than on day two (40.54 ± 2.01%; CI: 40.11–40.96, $p < 0.01$, $d = 0.27$).

**Table 2.** Uni-axial contributions to $PL_{TOTAL}$ across stages of the ballet-specific choreograph. Values are mean ± σ.

| | | Accelerometer Metric | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $PL_{Total}$ | | $PL_{AP}$ % | | $PL_{ML}$ %$^{\dagger}$ | | $PL_{V}$ %$^{\dagger}$ | |
| Stage | Unit location | Day 1 | Day 2 | Day 1 | Day 2 | Day 1 | Day 2 | Day 1 | Day 2 |
| 1 | C7 | 32.56 ± 5.83 | 29.87 ± 6.86 | 25.91 ± 2.30 | 25.99 ± 3.98 | $15.78^{\delta\eta}$ ± 1.57 | $16.56^{\delta\eta}$ ± 1.87 | $58.31^{*\eta}$ ± 3.33 | $57.45^{*\eta}$ ± 4.49 |
| | DL | 133.42 ± 26.92 | 115.56 ± 20.97 | 27.09 ± 1.01 | 28.11 ± 1.54 | $36.17^{\delta}$ ± 2.51 | $36.65^{\delta}$ ± 1.98 | $36.73^{\delta}$ ± 2.73 | $35.23^{\delta}$ ± 1.87 |
| | NDL | 129.10 ± 21.33 | 112.37 ± 20.94 | 27.09 ± 1.77 | 27.90 ± 1.87 | $35.54^{\delta}$ ± 2.00 | $36.71^{\delta}$ ± 2.18 | $37.37^{\delta}$ ± 2.20 | $35.40^{\delta}$ ± 1.54 |
| 2 | C7 | 29.94 ± 3.87 | 28.40 ± 3.65 | $25.73^{\eta}$ ± 2.31 | $24.99^{\eta}$ ± 1.72 | $20.74^{\delta\eta 1}$ ± 1.85 | $21.61^{\delta\eta 1}$ ± 2.01 | $53.53^{*\eta 1}$ ± 2.65 | $53.40^{*\eta 1}$ ± 2.90 |
| | DL | 136.03 ± 27.11 | 122.50 ± 13.60 | 26.66 ± 0.69 | 27.79 ± 0.67 | $36.54^{\delta}$ ± 1.12 | $36.80^{\delta}$ ± 1.97 | $36.80^{\delta}$ ± 1.39 | $35.41^{\delta}$ ± 1.90 |
| | NDL | 136.46 ± 18.23 | 119.51 ± 12.84 | 26.74 ± 1.07 | 27.20 ± 1.05 | $35.22^{\delta}$ ± 1.05 | $36.59^{\delta}$ ± 1.74 | $38.05^{\delta}$ ± 0.69 | $36.81^{\delta}$ ± 1.30 |
| 3 | C7 | 35.69 ± 4.57 | 35.69 ± 4.18 | $25.14^{\eta}$ ± 1.70 | $25.22^{\eta}$ ± 1.02 | $22.25^{\delta\eta 12}$ ± 1.48 | $22.56^{\delta\eta 12}$ ± 1.42 | $52.61^{*1}$ ± 2.35 | $52.21^{*1}$ ± 2.14 |
| | DL | 163.77 ± 26.92 | 152.12 ± 17.08 | 26.93 ± 0.56 | 28.61 ± 0.93 | $36.33^{\delta}$ ± 1.18 | $36.13^{\delta}$ ± 1.43 | $36.74^{\delta}$ ± 1.37 | $35.25^{\delta}$ ± 1.63 |
| | NDL | 163.96 ± 21.25 | 150.25 ± 20.95 | $28.49^{2}$ ± 1.46 | $28.61^{2}$ ± 1.25 | $34.48^{\delta 2}$ ± 1.14 | $35.68^{\delta 2}$ ± 1.62 | $37.03^{\delta 2}$ ± 1.08 | $35.71^{\delta 2}$ ± 1.22 |
| 4 | C7 | 38.87 ± 5.14 | 37.89 ± 6.50 | $24.87^{\eta}$ ± 2.23 | $24.68^{\eta}$ ± 0.98 | $24.69^{\eta 123}$ ± 1.24 | $25.14^{\eta 123}$ ± 1.45 | $50.44^{*123}$ ± 2.51 | $50.18^{*123}$ ± 2.13 |
| | DL | 183.40 ± 34.85 | 172.65 ± 23.38 | $28.54^{23}$ ± 1.38 | $29.56^{23}$ ± 1.08 | $36.80^{\delta}$ ± 1.20 | $36.79^{\delta}$ ± 1.60 | $34.65^{*23}$ ± 0.89 | $33.64^{*23}$ ± 1.72 |
| | NDL | 185.00 ± 28.85 | 167.08 ± 25.48 | $29.24^{2}$ ± 1.42 | $29.28^{2}$ ± 1.24 | $35.60^{\delta 3}$ ± 1.12 | $37.18^{\delta 3}$ ± 1.56 | $35.16^{*123}$ ± 1.25 | $33.54^{*123}$ ± 1.58 |
| 5 | C7 | 39.33 ± 5.83 | 40.12 ± 7.91 | $25.11^{\eta}$ ± 1.58 | $25.14^{\eta}$ ± 1.02 | $25.54^{\eta 1234}$ ± 1.31 | $25.77^{\eta 1234}$ ± 1.32 | $49.34^{*1234}$ ± 2.01 | $49.08^{*1234}$ ± 1.80 |
| | DL | 184.24 ± 30.73 | 181.19 ± 26.63 | $30.01^{1234}$ ± 1.43 | $30.52^{1234}$ ± 1.19 | $36.76^{\delta}$ ± 1.37 | $37.16^{\delta}$ ± 1.45 | $33.23^{*1234}$ ± 1.59 | $32.33^{*1234}$ ± 2.19 |
| | NDL | 185.05 ± 27.23 | 177.33 ± 27.26 | $30.27^{1234}$ ± 1.17 | $30.43^{1234}$ ± 1.99 | $35.67^{\delta}$ ± 0.95 | $36.60^{\delta}$ ± 0.98 | $34.06^{*123}$ ± 1.47 | $32.96^{*123}$ ± 1.81 |

C7, 7th cervical vertebrae; DL, dominant limb; NDL, non-dominant limb, $PL_{TOTAL}$ (accumulated load); $PL_{AP}$ %, percentage contribution of anterior-posterior acceleration; $PL_{ML}$ %, medial-lateral acceleration; $PL_{V}$ %, vertical acceleration. $^{\dagger}$ denotes a significant between-day difference. $^{\eta}$ denotes a significant difference between C7 and the lower-limbs. * denotes a significant difference compared with $PL_{AP}$ % and $PL_{ML}$ %. $^{\delta}$ represents a significant difference to $PL_{AP}$. $^{12345}$ signify the pairwise comparisons from stage 1 ($^{1}$) through to stage 5 ($^{5}$).

The significant unit position *x* uni-axial contribution interaction ($p < 0.01$) demonstrated that $PL_{AP}$ at C7 (25.28 ± 1.88%; CI: 24.75–25.80) was significantly lower than both the dominant (28.38 ± 1.05%; CI: 28.05–28.71, $p < 0.01$, $d = 0.71$) and non-dominant (28.52 ± 1.43%; CI: 27.89–29.16, p < 0 01, $d = 0.70$) limb. There was no significant bilateral difference (p = 1.00). $PL_{ML}$ was also significantly lower at C7 (22.07 ± 1.55%; CI: 21.22–-22.92) compared with the dominant (36.61 ± 1.58%; CI: 36.10–37.13, p = 0.001, *d* = 0.98) and non-dominant (35.93 ± 1.43%; CI: 35.19–36.67, p < 0.01, *d* = 0.98) limb, with no significant bilateral asymmetry (p = 0.19). $PL_V$ at C7 (52.66 ± 2.63%; CI: 51.52–53.79) was significantly higher than the dominant (35.00 ± 1.72%; CI: 34.34–35.67, p = 0.001, *d* = 0.97) and non-dominant limb (35.55 ± 1.41%; CI: 34.86–36.24, p < 0.01, *d* = 0.97), with no significant bilateral difference (p = 0.74).

There were significant stage *x* unit position (p = 0.04), stage *x* uni-axial contribution (p < 0.01), and stage *x* unit position *x* uni-axial contribution (p < 0.01) interactions. Post-hoc analyses showed that at C7, $PL_{AP}$ remained constant throughout the duration of the protocol (p ≥ 0.23), whereas $PL_{ML}$ increased significantly between stages (p ≤ 0.03, *d* = 0.-27–0.81). A compensatory trend was observed for $PL_V$, with significant (p ≤ 0.01, *d* = 0.-25–0.51) progressive decreases demonstrated as a function of exercise duration, with the exception of stage 2 to stage 3 (p = 0.18). In the dominant limb, $PL_{ML}$ did not significantly alter during completion of the ballet-specific choreograph (p ≥ 0.65). $PL_{AP}$ increased significantly from stage 4 to stage 5 (p ≤ 0.01, *d* = 0.43), whilst $PL_V$ significantly decreased from stage 3 onwards (p ≤ 0.01, *d* = 0.39–0.55). In the non-dominant limb, $PL_{AP}$ increased significantly from stage 2 onwards (p ≤ 0.001, *d* = 0.35–0.59), expect between stage 3 and stage 4 (p = 0.07). $PL_{ML}$ was significantly greater in stage 2 (35.91 ± 1.39%; CI: 35.12–36.69) compared with stage 3 (35.08 ± 1.38%; CI: 34.21-35.95, p = 0.04, *d* = 0.29). $PL_V$ significantly decreased temporally from stage 2 (p ≤ 0.04, *d* = 0.33–0.62) except between stage 4 and stage 5 (p = 0.08).

### Physiological responses

HR and RPE responses to the ballet-specific choreography are presented in Table 3. A significant main effect for stage demonstrated that HR increased significantly from stage 1 to stage 2 (p = 0.001, *d* = 0.25), and stage 2 to stage 3 (p = 0.01, *d* = 0.25), whilst RPE (p ≤ 0.01, *d* = 0.27–0.39) increased significantly as function of exercise duration. However, there were no significant between-day differences for HR (p = 0.53) or RPE (p = 0.33), nor a significant day *x* stage interaction for HR (p = 0.09) or RPE (p = 0.79).

## Discussion

The primary aims of the current investigation were to quantify the within– and between-day load responses to a ballet-specific testing protocol, whilst examining the influence of

**Table 3.** Temporal effects on HR and RPE during the ballet-specific protocol. Values are mean ± σ.

| | Heart Rate | | Rating of Perceived Exertion | |
|---|---|---|---|---|
| Stage | Day 1 | Day 2 | Day 1 | Day 2 |
| 1 | 161.10 ± 20.91 | 158.00 ± 25.63 | 12.90 ± 2.92 | 11.80 ± 3.33 |
| 2 | 171.90 ± 23.00[1] | 170.90 ± 21.66[1] | 14.60 ± 2.84[1] | 13.80 ± 3.19[1] |
| 3 | 181.40 ± 14.27[12] | 181.00 ± 14.95[12] | 16.50 ± 2.22[12] | 15.80 ± 1.99[12] |
| 4 | 184.50 ± 9.41[12] | 185.50 ± 16.20[12] | 17.30 ± 1.70[123] | 17.20 ± 1.81[123] |
| 5 | 188.90 ± 14.79[123] | 187.90 ± 13.19[123] | 18.50 ± 1.18[1234] | 18.5 0 ± 1.08[1234] |

[12345]denotes a significant difference between stages from stage 1 ([1]) through to stage 5 ([5]).

unit location with a specific focus on bilateral loading asymmetries in ballet dancers. The ballet-specific choreographed routine was designed in accordance with the constructs of the petit and grand allegro routines of ballet.

Within-day accelerometer-derived load responses to a novel ballet-specific choreograph increased as product of time and intensity of exercise. $PL_{TOTAL}$ demonstrated a progressive increase over completion of the testing protocol, a trend consistent with the findings of previous research conducted during the DAFT protocol (Brogden et al., 2018). Increases in accelerometer-derived load followed the same temporal pattern to those quantified for HR and RPE, thereby suggesting that resultant load responses reflected the physiological and perceptual rigours of the current testing protocol. Relative contributions to $PL_{TOTAL}$ revealed a significant uni-axial contribution *x* stage interaction. During stage 1, the ratio of accelerations in $PL_{AP}$, $PL_{ML}$ and $PL_{V}$ was 27:30:43, which by stage 5 had altered to 29:32:39. The higher contribution from the vertical plane may be indicative of the number of aerial displacements (e.g., Jeté, Temps levé) included in the ballet protocol. That compensatory increases in $PL_{AP}$ and $PL_{ML}$ for a reduction in $PL_{V}$ in stage 5 were apparent despite the greater number of jump-landing manoeuvres, may suggest an altered movement strategy was employed. This notion is supported by research showing that soccer players adopt a running technique to lower their centre of mass and reduce vertical accelerations following increases in external and internal load (Cormack et al., 2013). The temporal increases in $PL_{TOTAL}$ may, in part, be explained by the progression of movement complexity and tempo as exercise duration increased. However, alterations in the contribution to overall movement from each plane may be symptomatic of fatigue-induced adjustments in technique when performing ballet-specific manoeuvres and/or routines (Fitzpatrick et al., 2019).

A second key finding highlighted a significant day *x* uni-axial contribution interaction, with relative contributions in $PL_{ML}$ increasing on day 2 to compensate for a lower contribution in $PL_{V}$. The experimental protocol required the same 20 minute choreographed routine to be completed twice, with 24-hours separating the two performances. There was no significant change in $PL_{TOTAL}$, or indeed the physiological or perceptual responses between days, and thus, the differences in planar contributions suggest an altered loading response. The reduced proportion of $PL_{V}$ may be a residual fatigue response as dancers attenuate their commitment to jump-landings in an effort to lower resultant impact forces (Fitzpatrick et al., 2019). This observed modification in movement strategy may have implications for performance aesthetics and training workload prescription. Ballet dancers expend numerous hours developing, learning, and perfecting routines, and may be required to execute the complex and mechanically demanding movement profile of ballet multiple times a day, across several days of the week (Wyon & Koutedakis, 2013). The injury risk when performing repeated jump-landing manoeuvres of high kinetic demand is magnified considering the limited time designated for recovery during a typical workday (Twitchett et al., 2010). With the majority of injuries in ballet attributed to overuse (Smith et al., 2015), conducting more prolonged observations of training and/or performance in ballet with emphasis on loading strategy responses to similar routines, may reveal key injury aetiology information (Bowen et al., 2017; Colby et al., 2014).

A further key finding was the significant main effect for unit position on $PL_{TOTAL}$ and the relative uni-axial contributions. Using a single unit to measure whole-body accelerations is therefore flawed given the multi-segment requirements of most movements (Nedergaard et al., 2017). These findings corroborate those of previous studies in cricket (Greig & Nagy, 2017) and in dance (Brogden et al., 2018). Hence, quantifying accelerometer-derived load using the conventional C7 placement may underestimate the interpretation of performance rigours in athlete monitoring, leading to inappropriate interventions. $PL_{TOTAL}$ showed an increase proportionate to the duration and intensity of exercise, with more profound increases observed in the lower-limbs. At C7, $PL_{TOTAL}$ was 4.6 times lower compared with the lower-limbs. In addition, $PL_{TOTAL}$ at C7 increased by approximately 27% between stage 1 and stage 5, which was markedly lower than the increases observed in the dominant (~47%) and non-dominant (~50%) limbs. The symmetry in load response demonstrated in the lower-limbs may reflect the emphasis on equal limb contribution and control during development, which typically begins at an early age (Bronner & Ojofeitimi, 2006).

The ratio of the uni-planar contributions to $PL_{TOTAL}$ at C7 (25:22:53) contrasted to that of the dominant (28:37:35) and non-dominant (28:36:36) limb. The higher relative contribution of $PL_{AP}$ and $PL_{ML}$ observed in the lower-limbs may be explained by the technique required to execute the discrete intricacies of ballet routines. For example, the Jete requires a forward split formation of the legs which is likely to result in greater anterior-posterior acceleration at the lower-limbs. Another observation was greater consistency in planar contributions to loading at stage 1 through to stage 5 in the lower-limbs (28:36:36 vs 30:37:33), compared with C7 (26:16:58 vs 25:26:49).

These findings suggest that accelerometers present an efficacious means of monitoring in-vivo loading during dance performance, but with consideration required for unit placement. However, the application of these findings are limited to the current experimental design, acknowledging the relatively short duration of the choreographed routine in relation to typical ballet training and performance demands. Meaningful inferences on the cumulative effects of training and/or performance on accelerometer-derived load may only be achieved via longitudinal observations spanning several weeks or months. It must also be noted that without a direct measure of neuromuscular fatigue, accelerometry may only serve as a proxy measure of fatigue, and the findings from the curent study ought to be interpreted with this in mind. Efforts to establish a direct association between neuromuscular fatigue and accelerometer-derived load responses are advocated. Dance genre, level of performer, and the impact of previous injury also warrant further investigation.

## Conclusion

Within-trial changes in tri-axial loading response were sensitive to the temporal increases in mechanical demand, suggesting efficacy in monitoring dancers. However, anatomical placement influences load magnitude, and planar contributions to loading should be considered in practice. Between-trial differences across consecutive days in planar contributions to $PL_{TOTAL}$ suggest an altered loading strategy. Of note, the magnitude of $PL_{TOTAL}$ was consistent between trials, highlighting the limitations of dependence on this single metric, which might mask planar changes with implications for technical performance and subsequent injury risk. There was no evidence of bilateral asymmetry in lower-limb loading, suggesting that ballet training facilitates physical symmetry.

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## Ethical approval

The University's departmental ethics committee granted approval of this study.

## Disclosure of potential conflicts of interest

No potential conflict of interest was reported by the author(s).

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## Notes on contributors

***Philip Nagy*** is a Lecturer in Sport & Exercise Therapy at York St. John University where he teaches on the Laboratory- and Field-based Assessment, Applied Sport and Exercise Biomechanics, Sports Injury Prevention, and Sports Injury Reconditioning and Return to Sport modules.

***Dr. Chris Brogden*** is a Senior Lecturer in Sport and Exercise Kinesiology and member of the Sports Therapy team where he lectures on Kinesiology and Research Methods based modules, whilst assisting in the functional rehabilitation clinic. Chris is currently supervising students at both masters and doctoral levels. In addition to this, Chris is currently a member of the departments' research and retention committees.

***Gabrielle Orr*** is a visiting Lecturer at Edge Hill University, involved with various modules on the BA (Hons) Dance degree programme. Gabrielle is a Distinction-grade MSc Dance Science graduate of the University of Wolverhampton. Gabrielle has over 15 years of dance experience in a variety of genres, and is currently performing with Ballet Folk UK.

***Professor Matt Greig*** is a Professor of Sports Therapy and a member of the senior management team in the Department of Sport and Physical Activity. Matt teaches on the Sports Therapy programme and is actively involved with postgraduate supervision at masters and PhD level. Matt leads the Sports Injuries research group which includes therapists and biomechanists.

## ORCID

Philip Nagy http://orcid.org/0000-0003-0564-510X
Chris Brogden http://orcid.org/0000-0001-8848-2048

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