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Force-time characteristics of repeated bouts of depth jumps and the effects of compression garments

Freddy Brown MSc [1,2], Matt Hill, Ph.D.[1], Derek Renshaw Ph.D.[3], Jason Tallis, Ph.D.[1]

[1] Research Centre for Physical Activity, Sport and Exercise Science, Coventry University, Coventry, UK
[2] School of Life Sciences, Coventry University, Coventry, UK
[3] Centre Health and Life Sciences, Coventry University, Coventry, UK

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Corresponding author:
Freddy Brown,
Coventry University,
Room 1.31, Alison Gingell Building,
Whitefriars Street, Coventry, CV1 2DS
Email: ad1385@coventry.ac.uk

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Abstract

No studies have reported ground-reaction force (GRF) profiles of the repeated depth-jump (DJ) protocols commonly used to study exercise-induced muscle damage (EIMD). Furthermore, whilst compression garments (CG) may accelerate recovery from EIMD, any effects on the repeated-bout effect are unknown. Therefore, we investigated the GRF profiles of two repeated bouts of damage-inducing DJs, and the effects of wearing CG for recovery. Non-resistance trained males randomly received CG (n=9) or placebo (n=8) for 72 h recovery, following 20 x 20 m sprints and 10 x 10 DJs from 0.6 m. Exercise was repeated after 14 days. Using a three-way (set x bout x group) design, changes in GRF were assessed with ANOVA and statistical parametric mapping (SPM). Jump height, reactive strength, peak and mean propulsive forces declined between sets ($p<0.001$). Vertical stiffness, contact time, force at zero velocity and propulsive duration increased ($p<0.05$). According to SPM, braking (17–25% of the movement), and propulsive forces (58–81%) declined ($p<0.05$). During the repeated bout, peak propulsive force and duration increased ($p<0.05$), whilst mean propulsive force ($p<0.05$) and GRF from 59–73% declined ($p<0.001$). A repeated bout of DJs differed in propulsive GRF, without changes to the eccentric phase, or effects from CG.

Introduction

Unaccustomed exercise, particularly that featuring eccentric (or lengthening) contractions, commonly results in myofibrillar disruption and impaired force-generating capacity, known as exercise-induced muscle damage (EIMD) [1]. The effects on untrained participants are severe, with strength deficits commonly exceeding 50% of pre-exercise values, and muscle soreness persisting in some cases for over 7 days [2]. As the effects of EIMD are exercise-specific [3-5] it is necessary for researchers to characterize the exercise challenges employed to aid standardisation and comparisons between studies. Repeated depth-jumps (DJs) are commonly used for this purpose [6,7] and, as the severity of EIMD is related to the force, velocity and work performed during eccentric contractions [3-5], protocols featuring more repetitions [8], from greater heights (and resulting impact velocities) are known to elicit more severe damage [9]. Consequently, a protocol consisting of 100 DJs (usually separated into 10 sets of 10) from a 0.6 m platform [6,7], is commonly used to study EIMD. However, no studies to date have characterized the force-time (F-T) profile of this damaging DJ protocol.

In addition to quantifying exercise loads, assessing the F-T profile of vertical jumps allows for a multifaceted description of neuromuscular function to characterize fatigue and recovery [10]. For example, as jump height is dependent on the magnitude and rate of lower-body force development [11], decrements induced by repeated DJs indicate the severity of EIMD [12-14]. Analysing drop-jump performance, specifically (rebounding from the floor as high and as rapidly as possible, on landing), sheds further light on the functional capabilities of the lower limb. For instance, measures of reactive strength index (RSI - defined as jump height divided by contact time), and vertical stiffness (force per unit of extension) are commonly used to highlight muscular qualities associated with acceleration, agility, and stretch-shortening function [15,16]. Furthermore, given that neuromuscular fatigue may manifest as strategic changes to preserve performance, the analysis of complete F-T jump profiles allows for a more detailed description of fatigue, that is more sensitive to change than analysing a given performance outcome in isolation [13,14,17,18]. Accordingly - in addition to drop-jump height - peak and average forces, as well as the durations of the eccentric and concentric phases are frequently reported alongside contact time, displacement/countermovement depth and RSI to monitor performance and recovery [13,15,16]. However, detailed descriptions of the effects of repeated DJs are lacking. Whilst several studies have reported changes in jump height using rudimentary methods [19-21], no research has yet reported the entire F-T profile of fatiguing DJs over repeated sets, needed to describe neuromuscular and strategic changes.

Much research has been carried out on potential recovery strategies for EIMD [6,7,22], with the use of compression garments (CG) demonstrating promising results [22,23]. However, accumulating evidence suggests that interventions which enhance acute recovery by ameliorating physiological stressors (e.g. inflammation/oxidative stress) can undermine adaptation [24,25]. Few studies have analysed the effects of CG on muscular adaptation, with equivocal findings to date [26-28]. In particular, evidence detailing the effects of recovery interventions on the rapid protective adaptations to EIMD known as the “repeated-bout effect” (RBE) [6,7,28] is scarce. This phenomenon describes the adaptations to unfamiliar exercise, which reduce the damage incurred by subsequent bouts [29], and is also (at least in part) mediated by inflammatory responses [29,30]. Such adaptations are highly desirable in the initial stages of training, so that subsequent exercise-performance and training adaptations can be optimized [31]. Importantly, firm conclusions on RBE require that damage is compared following two identical bouts, with repeated DJs commonly used to provide a standardized stimulus [6,7]. However, it is unknown whether repeated bouts of DJs provide equivalent stresses, or whether physiological and technical adaptations render them mechanically distinct [29,32-34]. For instance, RBE is associated with musculotendinous adaptations [29,33,34], while adaptive improvements in complex task performance also commonly involve technical changes [18,35]. Research is therefore required to compare the F-T profiles of repeated bouts of DJs.

Whilst research on recovery and adaptation commonly focuses on discrete performance outcomes [1,22,23], physiological responses to exercise are frequently accompanied by altered movement strategies throughout complex tasks [13,14,17,18]. Indeed, analysing complete movements may be more sensitive to change than comparing discrete neuromuscular outcomes, with adaptations in countermovement jump (CMJ) mechanics observed in the absence of changes in peak force or velocity [36]. Such analyses are further aided by statistical approaches which permit comparisons of complete wave-forms, with statistical parametric mapping (SPM) [37] one such technique previously used to compare differences in jump strategies [36]. Although we recently reported that using CG for recovery blunted RBE for isokinetic performance [28] the implications for complex movements remain unclear. Accordingly, the aims of the current study were to 1) Characterize the average F-T profile of 10 repeated DJs from 0.6 m, 2) Investigate differences in discrete neuromuscular indices between 10 successive sets, as well as to compare complete F-T profiles between sets using SPM, 3) Assess any changes in neuromuscular indices or F-T profiles between two repeated bouts of DJs, 4) Investigate whether any changes between bouts or sets were influenced by wearing CG during recovery from an initial bout. It was hypothesized that neuromuscular performance (namely jump height and propulsive force) would decline between sets, with deteriorations ameliorated over the repeated bout. The effects of CG on RBE were assessed by comparison with a control group, using the null hypothesis that no differences would be observed (two-tailed).

Methods

Study design:

The current study set out to characterize the fatiguing DJ protocol employed as part of a larger project assessing the effects of CG on exercise recovery and RBE [28]. Average ground-reaction force (GRF) profiles were compared between 10 sets of 10 DJs, repeated over two bouts (B1 and B2), in two groups of participants, using a three-way design (set x 10 – repeated measures; bout x 2- repeated measures; group x 2 – independent groups). Following baseline performance tests, participants completed damaging exercise, before being randomly allocated either CG or placebo tablets (PLA) for 72 h recovery (Figure 1). Interventions were allocated by a third party without the knowledge of the lead researcher [28]. Participants were told tablets contained magnesium to aid recovery and that there was an additional control group for comparison. This group did not exist. Participants were informed of deception and questioned on adherence after data collection was completed via email, using a standardized email template. Exercise was repeated after 14 d without any intervention [6,7,28,38]. A sample-size calculation was carried out using the MorePower 6.0.4 software package, based on an effect-size of 0.36, previously reported to describe magnitudes of RBE in the lower body [39]. A minimum sample of n=16 (2 x n=8) was required to achieve 80% statistical power with an alpha value of 0.05. This was sufficient to detect an effect size of 0.14 from a three-way interaction (ANOVA), basing the calculation on two independent groups, completing two bouts of nine sets of DJs (as only single-digit figures may be entered into Morepower). At the conclusion of the trial, participants rated their interventions for perceived efficacy from 0 to 10 (half-marks accepted) using a modified procedure to evaluate the effectiveness of blinding [40]. Specifically, participants were asked “How effective was your intervention from 0 to 10 (half-marks allowed)?”, with 0 described as “no-intervention, or placebo”, and 10 as “the most effective intervention you can imagine (for instance a drug)”.

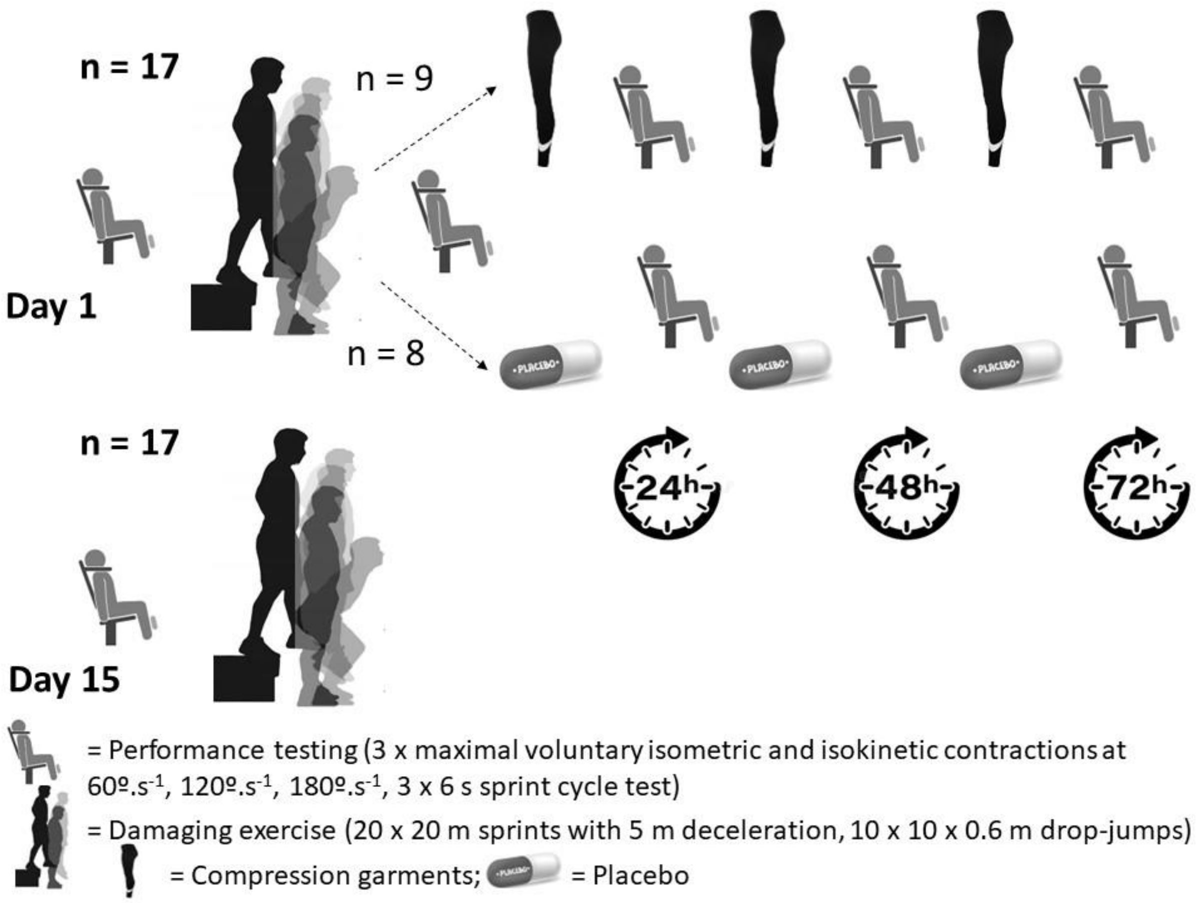


Figure 1. Study design

Participants:

Informed consent was provided by all participants following institutional ethical approval. To limit the variation in EIMD responses [38], only male participants (18–45 years) were recruited who had not completed weights-training for ≥6 months. Participants were physically active, completing 4±4 exercise bouts per week (with a median and interquartile range of 3 and 7 sessions, respectively), including running (n=10) non-load bearing exercise (n=4; swimming and cycling), and intermittent sports (n=6; football, boxing training), and ranged from recreational exercisers to competitive athletes (n=6). Participants had not suffered injuries that influenced habitual exercise for ≥4 weeks and had not consumed anti-inflammatory medications within 24 h of the trial [28]. Full data sets were processed for 17 participants (GC n=9; PLA n=8), for whom data was obtained from all 10 sets, with a maximum of 1 jump per set missing (technical error - n=2). However, as the assumptions of SPM require a balanced design, one participant was removed from the CG group for analysis. This participant was chosen as their body mass was over 2 SD lighter than the group average (55.6 kg), placing them outside of the 95% confidence limits for the sample. However, this omission made no difference to hypothesis testing, with the same results obtained if the heaviest participant was removed instead. Participant characteristics for CG and PLA were 76.0±7.0 kg, 1.79±0.09 m, 29.6±5.8 y and 76.4±7.4 kg, 1.78±0.07 m and 28.7±7.3 y, for body-mass, stature, and age, respectively. Participants were requested to record their dietary intake form the day before the trial and for 72 h recovery, then to replicate this for B2.

Exercise procedures:

Prior to fatiguing exercise, muscular performance was assessed with a previously described testing battery [41] as part of a trial on recovery [28], which included three repetitions of maximal isometric knee-extensions, isokinetic knee-extensions at three velocities (KinCom, Chattanooga, TN, USA – 100 Hz), and 6 s cycle sprints (Wattbike Pro, Wattbike Ltd., Nottingham, UK), following a standardized warm-up. Participants then undertook 100 DJs, preceded by 20 x 20 m sprints (TC PhotoGate, Brower timing Systems, Utah, USA), undertaken from a standing start, from immediately behind the light-gates (separated by 1m). One sprint was completed each minute before a rapid, 5 m deceleration and walking back to the start. Participants were told their times to encourage maximal effort and informed they would have to repeat sprints that continued beyond the marked 5 m deceleration. Immediately afterwards, 10 sets of 10 DJs (S1–S10) were completed [42] (one set every 2.5 min) from a 0.6 m box onto two force plates sampling at 1000 Hz (AMTI BP900900, Watertown, MA, USA). Arm swing was not permitted, with participants instructed to jump as high as possible with arms akimbo, and being warned they would have to repeat DJs for which the knee angle failed to reach 90^{o} flexion (three warnings) [20]. Baseline testing was repeated immediately post exercise, then daily for 72 h after each bout (Figure 1).

Depth-jump metrics:

Acceleration, velocity and displacement throughout each jump were calculated from changes in total, unfiltered vertical force using forward integration, assuming an impact velocity of 3.43 $m.s^{-1}$ from the 0.6 m drop [28,43]. A threshold of 10 N was used to identify contact and take-off, and jump height (m) calculated as: $(\text{take-off velocity})^2/2g$. Braking and propulsive phases were identified either side of the point of maximum displacement (i.e. the bottom of the countermovement), with eccentric and propulsive forces (peaks and means) examined to quantify eccentric load and performance deteriorations throughout exercise [11,13], respectively. Additionally, contact time, the durations of both eccentric and propulsive phases, as well as RSI (jump height/contact time) and vertical stiffness were calculated [13]. The principles of Hooke's law were used to calculate stiffness at the bottom of the countermovement by dividing force at zero velocity by the change in whole-body centre of mass, with both RSI and stiffness known to be sensitive to fatigue [13,18].

Recovery interventions:

Post-exercise, performance was re-tested, before participants immediately donned CG or took placebo in private. This procedure was repeated daily for 48 h, with interventions returned to the third party at 72 h. Participants in CG wore British class II graduated stockings (Medi UK Ltd., Hereford, UK), designed to apply 18–24 mmHg at the ankle, in line with recent positive findings [42]. Garments were worn for 72h, being removed only to wash [28]. In PLA, participants took one daily homeopathic “blank” pellet containing <0.1 g carbohydrate (6 mm hard lactose/sucrose tablets, HSC, Holt, UK) for 72h. Compression at the skin-garment interface was measured during familiarisation, prior to randomisation and group allocation, using a pneumatic pressure sensor (Picopress, Microlab, Padua, Italy) [41]. Average interface pressures of 18±3, 21±8, 16±2 mmHg were recorded in CG at the ankle, calf and thigh respectively – specifically at the B, C and F points as specified by industry guidelines [44] and reported previously [41]. Once data collection was completed, participant questioning revealed that all placebo tablets had been consumed, while CG were worn for an average of 21.0±3.6 $h.d^{-1}$.

Statistical analysis:

Average force and velocity traces for S1–S10 were derived for each participant and normalized into 101 time series data-points from initial contact to take-off. Force (absolute) and velocity profiles were compared between sets, bouts and groups by carrying out SPM on a three-way ANOVA, using the spm1d script [45] in MatLAB (The MathWorks Inc, R2018b, Natick, MA, USA). *Post hoc* analyses were carried out where interactions were found using multiple t-tests, adjusted using the Bonferroni correction. Significant differences for *post hoc* tests were reported only where the region of difference overlapped with the region identified for the interaction [37]. To aid graphical representation, 95% confidence intervals were calculated for comparisons between bouts, using the procedure previously described for repeated-measures designs [46]. Discrete DJ variables were assessed using a three-way ANOVA (SPSS28, IBM, NY, USA) for jump height, peak and average braking forces, peak and average propulsive forces, force at zero velocity (F0V), RSI, relative stiffness, and DJ depth. Alpha was set *a priori* at 0.05.

Results

No difference in perceived efficacy of conditions (CG = 4±2.5, PLA = 5±2) was noted between groups (t=0.972, *p*=0.347), suggesting blinding was effective. Average sprint times throughout the fatiguing protocol for CG were 3.47±0.24 s versus 3.56±0.34 s over B1 and B2, respectively, and 3.46±0.21 s versus 3.43±0.24 s for PLA. There were no differences between groups or bouts, nor any interactions (*p*>0.05). A significant effect of time was apparent (F=2.16, *p*=0.005), with *post hoc* testing indicating a lower time in the final sprint (3.41±0.24 s) compared with sprints 7, 15, 16, 17 and 19 (*p* from 0.004 to 0.05, 3.44±0.25 to 3.5±0.32 s).

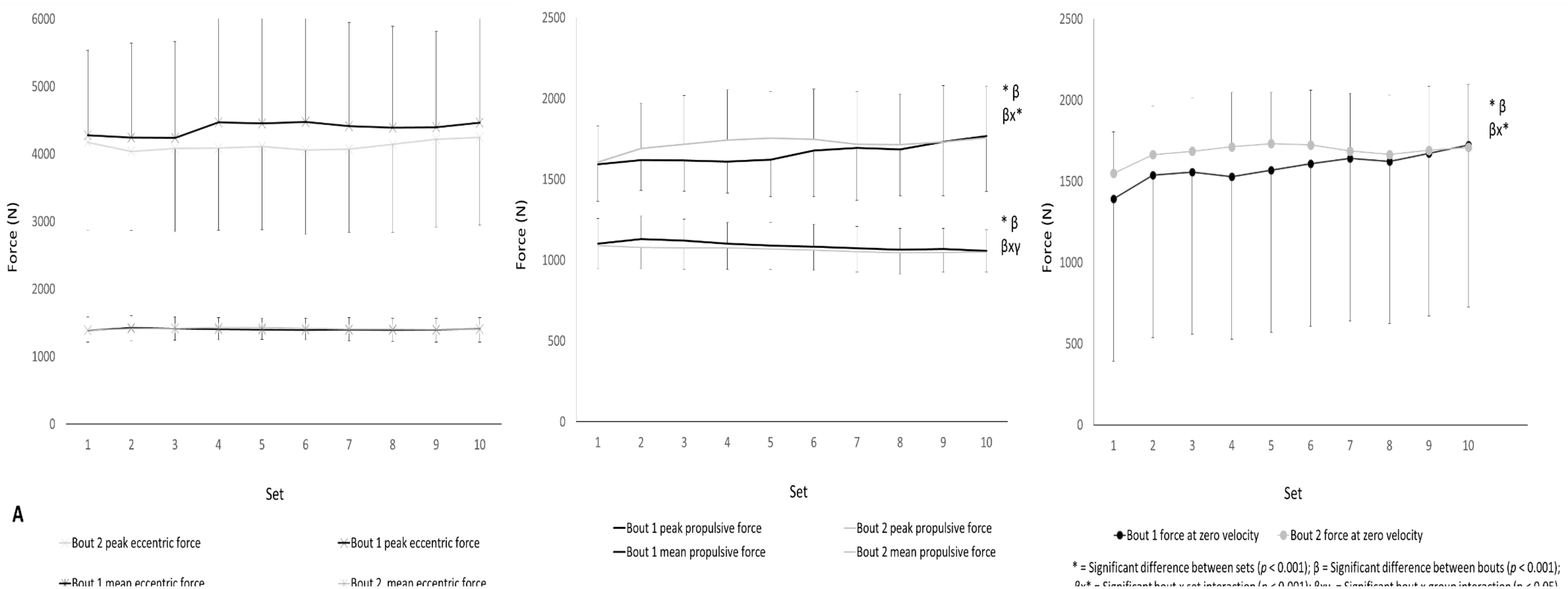
Multiple indices of neuromuscular function varied between sets. Both Jump height (F=14.452, *p*<0.001) and RSI (F=14.231, *p*< 0.001) declined, with *post hoc* analysis revealing reductions from S6 (Table 1). Conversely, the change in relative stiffness (F=3.373, *p*=0.039) belied an increase S1 to S3. Both DJ depth and F0V changed between sets (F=2.86, *p*=0.045 and F=6.474, *p*=0.01, respectively), although *post hoc* comparisons were not significant (Figure 2). Whilst peak and average propulsive forces changed between sets (F=4.252, *p*<0.031, F=18.621, *p*<0.001, respectively), *post hoc* differences were not significant (Table 1, Figure 2). No change in peak or average eccentric force was observed (F=1.452, *p*=0.238 and F=1.926 *p*=0.162, respectively). Contact time (F=4.102, *p*=0.006) and the duration of the propulsive phase (F=4.064, *p*=0.016) both changed between sets, with *post hoc* testing revealing significant increases compared to earlier sets in sets 8 and 10, respectively (Table 1). No change in eccentric duration was observed (*p*>0.05).

Analysis of GRF with SPM revealed changes between sets (0.001<*p*<0.007), with differences at 5-8%, 18–26%, 35–48%, 54–84% and 89–99% of the time series (Figure 4). *Post hoc* analysis revealed that initial braking forces (17–25% of the time series), as well as propulsive GRF from 58–81% both declined over the second half of each bout – (Figure 4). A significant change in velocity was shown with SPM between sets from 30 to 50% and 75 to 90% of the time series, with no other main effects of interactions. *Post hoc* analyses inferred a decline in propulsive velocity in later sets, with reductions after 80% evident in S8-S10 compared to S2-S5 (Figure 6).

Between bouts, no changes were observed in either peak (F=2.535, *p*=0.132) or average (F=0.575 *p*=0.46) eccentric forces. Conversely, peak propulsive force was greater in B2 (F=4.543, *p*=0.05), whilst average propulsive force declined (F=9.656, *p*=0.007). A set x bout interaction was observed for peak propulsive force (F=3.517, *p*=0.025), although no significant *post hoc* differences were observed (*p*>0.05). Force at zero velocity increased between bouts (F=9.42, *p*=0.008) with *post hoc* analysis of the set x bout interaction (F=3.466, *p*=0.039) demonstrating a delayed increase between sets in B2 (Table 1). Propulsive time was greater over B2 (F=6.358, *p*=0.023), resulting in a decline in RSI (F=4.602, *p*=0.049; Table 1). No difference in braking time was observed (*p*>0.05).

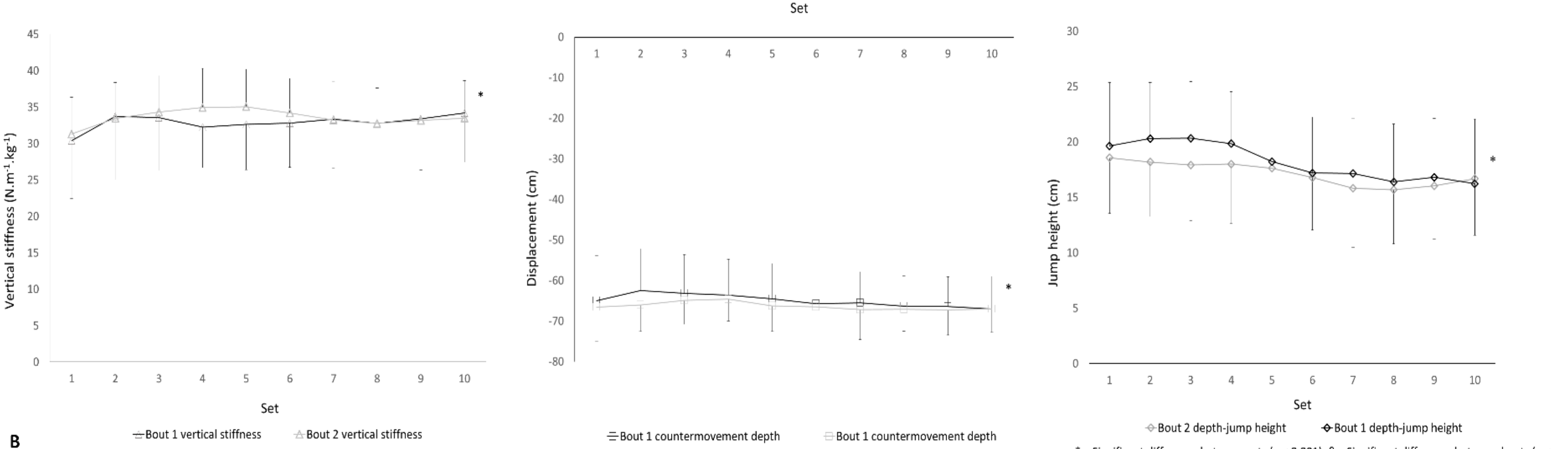
The use of SPM revealed changes in GRF between bouts. A decline from 59–73% of the jump was apparent, (*p*<0.001; Figure 3), although the trend towards increased GRF from 30–50% in B2 did not reach significance (0.9<F<1.2, *p*>0.05). Additionally, a bout x set interaction was observed (0.001<*p*<0.017) at regions spanning 50-73%, and 97–99%. *Post hoc* analysis revealed a decline in initial propulsive force between sets (~60–80%) over both bouts (Table 2). However, this decline appeared greater over B1, in which a significant reduction in GRF was observed between sets 7–9. This was not apparent in B2 (Table 2). Similarly, although GRF in the late propulsive phase (>70%) declined over B1 from S6, this decline was less apparent in B2, with only S9 and S10 displaying lower values than S1. Finally, forces at take-off (≥95%) recorded during B1S1 were higher than for all other jumps, in both bouts (Table 2). A group x set interaction for GRF was observed from 21–27% of the time series. However, *post hoc* analysis revealed no differences between groups, with a decline in CG between S4 and S5 being the only significant finding over this region (*p*<0.001).

No differences between groups were observed for any variables, other than a group x set interaction for braking time (F=2.138, *p*=0.03). However, *post hoc* differences were not significant (*p*>0.05).



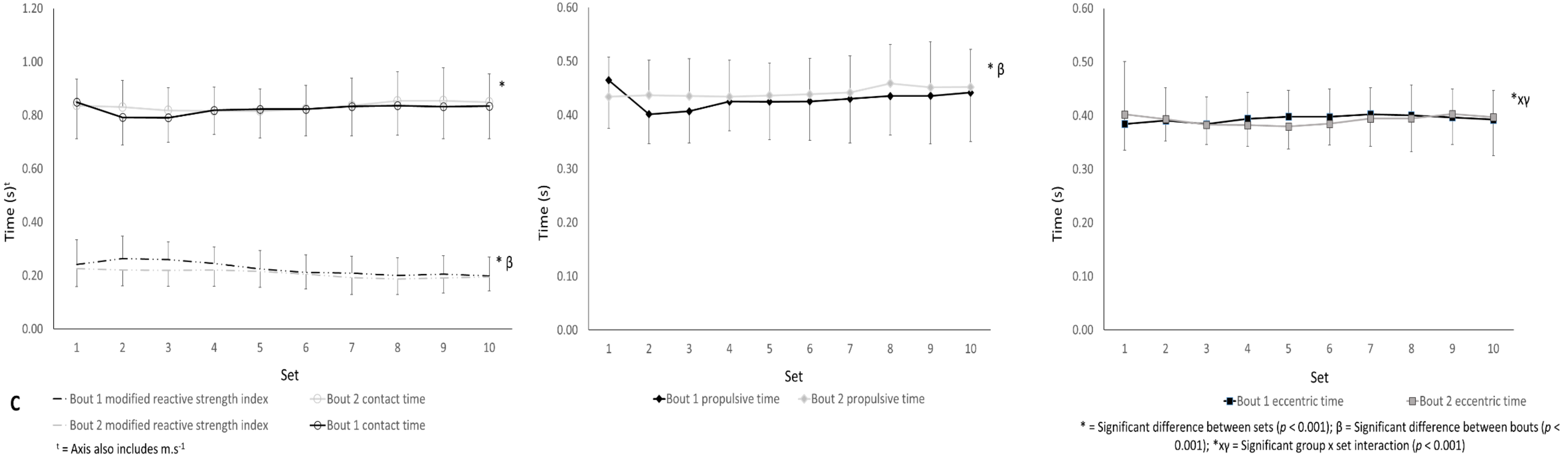
A

* = Significant difference between sets ($p < 0.001$); β = Significant difference between bouts ($p < 0.001$); βx* = Significant bout x set interaction ($p < 0.001$); βxγ = Significant bout x group interaction ($p < 0.05$)



B

* = Significant difference between sets ($p < 0.001$); β = Significant difference between bouts ($p < 0.001$); βx* = Significant bout x set interaction ($p < 0.001$)



ᵗ = Axis also includes m.s^{-1}

* = Significant difference between sets ($p < 0.001$); β = Significant difference between bouts ($p < 0.001$); *xγ = Significant group x set interaction ($p < 0.001$)

Figure 2. Significant changes in discrete jump variables over time

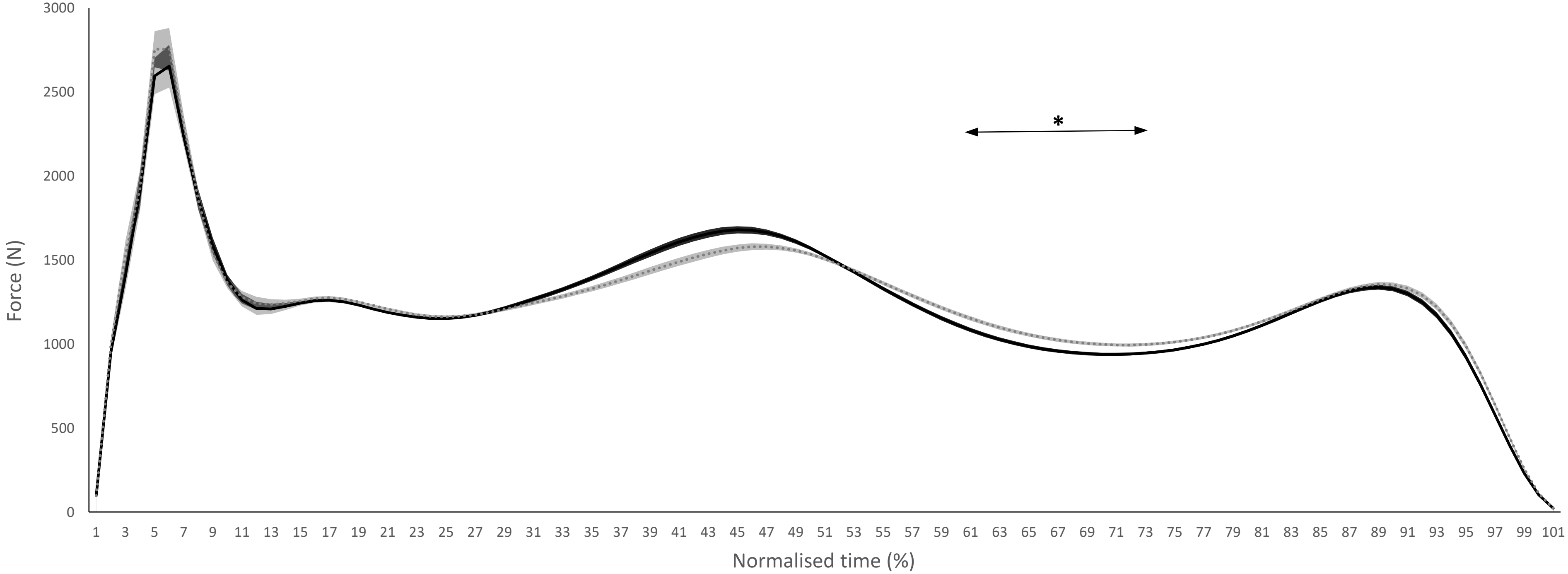


Figure 3. Average force-time profiles and 95% confidence intervals for 100 depth jumps over an initial and repeated bout

Grey dashed line = Bout 1 (95% confidence interval = grey shaded area); Black solid line = Bout 2 (95% confidence interval = black shaded area). * $p<0.001$

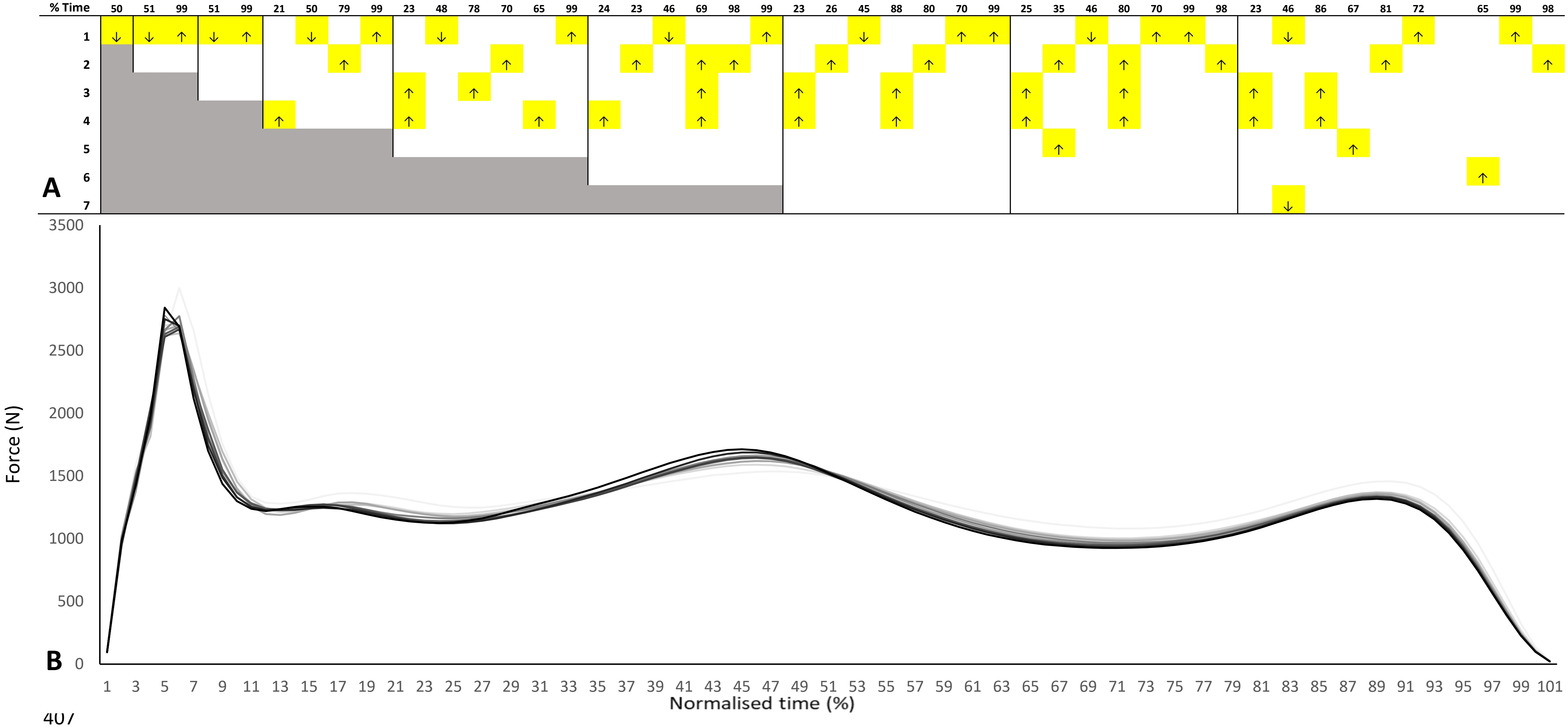
Table 1. Results of a three-way (group x bout x set) ANOVA for discrete depth jump indices

	Set		Bout		Bout x Set		Group		Group x set		Group x bout		Group x bout x set		Significant *post hoc* differences								
Measure	**F**	**p**	**F**	**P**	**F**	**P**	**F**	**p**	**F**	**P**	**F**	**P**	**F**	**P**	**Comparison**			**Set**	**6**	***7***	**8**	**9**	**10**
Jump height	14.5	<0.001	2.766	0.117	1.276	0.29	1.706	0.205	1.278	0.254	1.703	0.212	0.811	0.607	**Set**	**Set**	**Value (m)**		0.17 ±0.05	0.16 ±0.05	0.16 ±0.05	0.16 ±0.05	0.16 ±0.05
																1	0.19±0.05	>	-	0.039	0.017		-
																2	0.19±0.05	>	0.033	0.006	0.002	0.049	-
																3	0.19±0.05	>	0.023	0.002	<0.001	0.003	0.032
																4	0.19±0.05	>	0.004	<0.001	<0.001	<0.001	0.01
																5	0.18±0.05	>	-	0.023	0.005	-	-
																6	0.17±0.05	>	-	-	0.025	-	-
																		Set	**6**	***7***	**8**	**9**	**10**
RSI	14.231	<0.001	4.602	0.049	1.388	0.258	1.993	0.178	1.185	0.309	2.086	0.169	0.451	0.905	**Set**	**Set**	**Value (m.s^{-1})**		0.21 ±0.06	0.2 ±0.06	0.19 ±0.06	0.2 ±0.06	0.2 ±0.06
																1	0.23±0.08						
																2	0.24±0.08	>		0.005	0.002	0.011	
																3	0.24±0.07	>	0.013	<0.001	<0.001	<0.001	0.007
																4	0.23±0.06	>	0.016	<0.001	<0.001	<0.001	0.02
																5	0.22±0.06	>		0.01	0.002		
																6	0.21±0.06	>			0.015		
															Bout	**Bout**		**Bout**	**2**				
																1	0.23±0.07	<	0.21± 0.06				
																		Set	**2**	**3**			
Stiffness	3.373	0.039	0.775	0.393	1.62	0.194	0.046	0.832	1.156	0.329	0.181	0.677	0.507	0.868	**Set**	**Set**	**Value (N.m^{-2})**		34±7	34±6			
																1	31±7	<	0.037	0.022			
																			B1S1	**B2S1**	**B2S4**	**B2S5**	**B2S6**
F0V	6.474	0.01	9.42	0.008	3.466	0.039	0.37	0.552	0.574	0.816	0.202	0.66	0.151	0.998	**Bout x set**	**Set**	**Value (N)**	**Set**	1392± 211	1549± 255	1712± 335	1733± 315	1725± 337
																B1S1	1392±211	<					
																B1S2	1537±196	>	0.01				
																B1S3	1558±202	>	0.005				
																B1S4	1528±229	>	0.012		0.002		
																B1S5	1569±260	<				<0.001	
																B1S6	1609±315	<					0.024
																B2S1	1549±255	>	0.004		0.042	0.01	
															Bout	**Bout**		**Bout**	**2**				
																1	1585±300	<	1682±334				
																		Set	**8**				

Contact time	4.102	0.006	1.865	0.192	1.404	0.251	0.15	0.905	1.266	0.261	0.55	0.47	0.562	0.827	**Set**	**Set**	**Value (s)**		0.84±0.11
																3 <	0.8±0.09		0.042
																		Set	**10**
Propulsive time	4.064	0.016	6.358	0.023	2.766	0.075	0.663	0.428	1.494	0.156	1.06	0.319	0.625	0.774	**Set**	**Set**	**Value (s)**		0.45±0.08
																2 <	0.42±0.06		0.045
															Bout	**Bout**		**Bout**	**2**
																1	0.43±0.07		0.44±0.07
Braking time	0.61	0.603	0.241	0.631	0.834	0.48	0.937	0.348	2.138	0.03	0.008	0.929	0.234	0.898				**PLA**	
															Group x set	**CG**	**Value (N)**	**S10**	0.37± 0.06
																S10>	0.42±0.06	<	0.041
Depth	2.86	0.045	1.674	0.215	0.44	0.703	2.709	0.121	1.555	0.135	0.039	0.845	0.599	0.796					
F_{PBk}	1.452	0.238	2.535	0.132	0.746	0.561	2.53	0.133	1.764	0.081	0.319	0.581	0.471	0.892					
F_{AVEBk}	1.926	0.162	0.575	0.46	1.253	0.302	0.524	0.48	1.483	0.16	0.016	0.901	0.416	0.925					
F_{PROPk}	4.252	0.031	4.543	0.05	3.517	0.025	0.598	0.451	0.788	0.628	0.034	0.856	0.377	0.945	**Bout**	**Bout**	**Value (N)**	**Bout**	**2**
																1	1662±460	<	1718±489
F_{PROAve}	18.621	<0.001	9.656	0.007	1.816	0.174	0.039	0.847	1.106	0.363	4.867	0.043	0.91	0.519	**Bout**	**Bout**	**Value (N)**	**Bout**	**2**
																1	1090±281	>	1064±272

RSI= Reactive strength index, F0V=Force at zero velocity; B2=Bout 2; Stiffness=Vertical stiffness; Depth=Countermovement depth; F_{PBk}=Peak braking force (N);=F_{AVEBk}=Average braking force (N);= F_{PROPk}=Peak propulsive force (N);=F_{PROAve}=Average propulsive force (N). Reported *p* values are adjusted maintain a critical alpha value of 0.05 using the Bonferroni correction

Set	**2**	**3**		**4**		**5**				**6**						**7**						**8**							**9**							**10**									
% Time	**36**	**36**	**93**	**36**	**93**	**17**	**37**	**65**	**93**	**18**	**36**	**59**	**60**	**61**	**92**	**18**	**21**	**37**	**58**	**93**	**91**	**17**	**21**	**38**	**55**	**56**	**60**	**92**	**20**	**22**	**37**	**57**	**62**	**91**	**96**	**19**	**36**	**55**	**55**	**56**	**59**		**60**	**90**	**93**



% Time	50	51	99	51	99	21	50	79	99	23	48	78	70	65	99	24	23	46	69	98	99	23	26	45	88	80	70	99	25	35	46	80	70	99	98	23	46	86	67	81	72		65	99	98
1	↓	↓	↑	↓	↑		↓		↑		↓				↑			↓			↑			↓			↑	↑			↓		↑	↑			↓				↑			↑	
2								↑					↑				↑		↑	↑			↑			↑				↑		↑			↑					↑					↑
3										↑		↑							↑			↑			↑				↑			↑				↑		↑							
4						↑				↑				↑		↑			↑			↑			↑				↑			↑				↑		↑							
5																														↑									↑						
6																																											↑		
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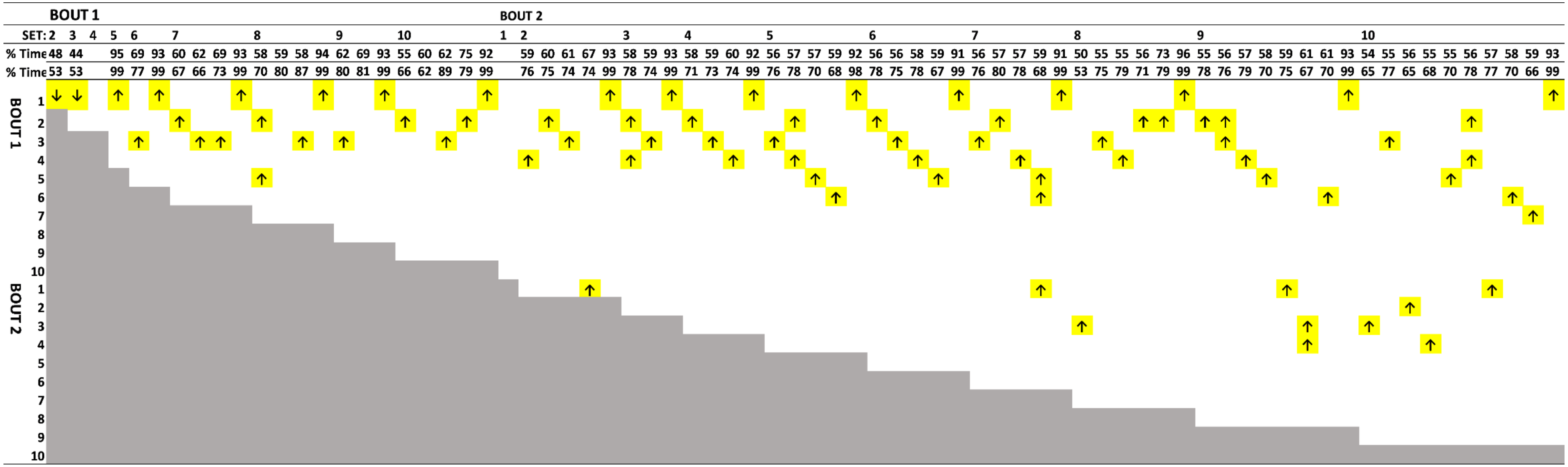
Figure 4. ***Post hoc*** **comparisons between average jump force values for 10 sets over two bouts of depth jumps, using statistical parametric mapping to identify regions of difference (% time series).**

A. ↑=Set indicated in the left-hand vertical column significantly higher than that indicated in the top horizontal row at specified region;↓= Set indicated in the left-hand vertical column significantly lower than that indicated in the top horizontal row at specified region. Third and fourth rows indicate the start and end of a region of difference (%). Adjusted alpha value=0.001 (45 comparisons).

B. *Post hoc* comparisons reported alongside individual force traces (confidence intervals omitted for clarity); Lines coloured more darkly in subsequent sets, with grey lines=sets 1–5; Black lines=sets 6-10



		BOUT 1																					
	SET:	2	3	4	5	6		7				8				9			10				
	% Time	48	44		95	69	93	60	62	69	93	58	59	58	94	62	69	93	55	60	62	75	92
	% Time	53	53		99	77	99	67	66	73	99	70	80	87	99	80	81	99	66	62	89	79	99
BOUT 1	1	↓	↓		↑		↑				↑				↑			↑					↑
	2							↑				↑							↑			↑	
	3					↑			↑	↑				↑		↑					↑		
	4																						
	5											↑											
	6																						
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	8																						
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	10																						
BOUT 2	1																						
	2																						
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	6																						
	7																						
	8																						
	9																						
	10																						

		BOUT 2																						
	SET:	1	2					3			4				5					6				
	% Time		59	60	61	67	93	58	59	93	58	59	60	92	56	57	57	59	92	56	56	58	59	91
	% Time		76	75	74	74	99	78	74	99	71	73	74	99	76	78	70	68	98	78	75	78	67	99
BOUT 1	1						↑			↑				↑					↑					↑
	2			↑				↑			↑					↑				↑				
	3				↑				↑			↑			↑						↑			
	4		↑					↑					↑			↑						↑		
	5																↑						↑	
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BOUT 2	1					↑																		
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	SET:	7					8						9								10									
	% Time	56	57	57	59	91	50	55	55	56	73	96	55	56	57	58	59	61	61	93	54	55	56	55	55	56	57	58	59	93
	% Time	76	80	78	68	99	53	75	79	71	79	99	78	76	79	70	75	67	70	99	65	77	65	68	70	78	77	70	66	99
BOUT 1	1					↑						↑								↑										↑
	2		↑						↑	↑		↑	↑											↑						
	3	↑						↑						↑							↑									
	4			↑					↑						↑											↑				
	5				↑											↑									↑					
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BOUT 2	1				↑												↑										↑			
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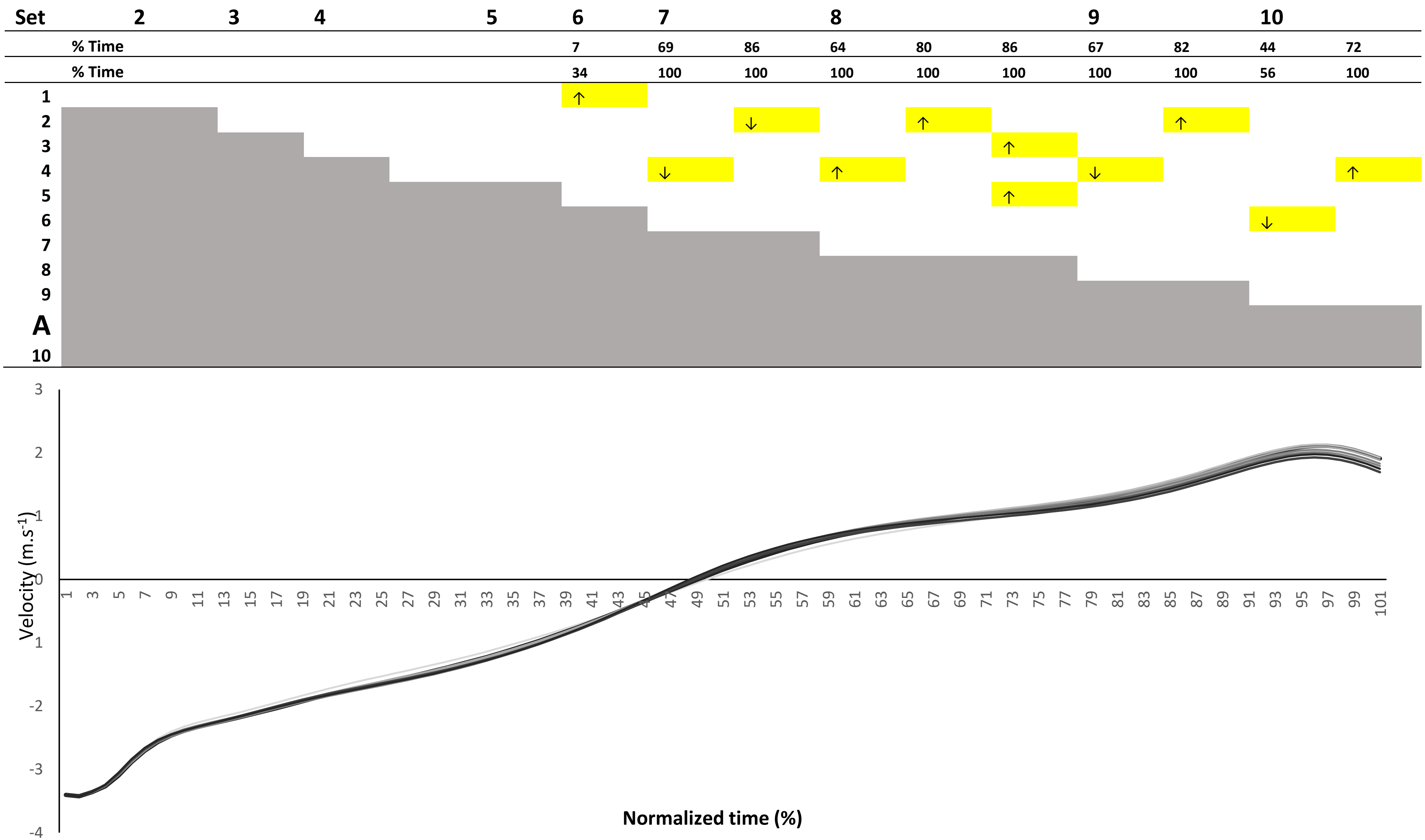
Figure 5. *Post hoc* analyses for the bout x set interaction found for jump force, using statistical parametric mapping to identify regions of difference (% time series)

↑=Set indicated in the left-hand vertical column significantly higher than that indicated in the top horizontal row at specified region;↓= Set indicated in the left-hand vertical column significantly lower than that indicated in the top horizontal row at specified region. Third and fourth rows indicate the start and end of a region of difference (%). Adjusted alpha value=0.0003 (190 comparisons).



Set	2	3	4	5	6	7		8			9		10	
% Time					7	69	86	64	80	86	67	82	44	72
% Time					34	100	100	100	100	100	100	100	56	100
1					↑									
2							↓		↑			↑		
3										↑				
4						↓		↑			↓			↑
5										↑				
6													↓	
7														
8														
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10														

Figure 6. ***Post hoc*** **comparisons between average jump velocity values for 10 sets over two bouts of depth jumps, using statistical parametric mapping to identify regions of difference (% time series)**

A. ↑=Set indicated in the left-hand vertical column significantly higher than that indicated in the top horizontal row at specified region; ↓= Set indicated in the left-hand vertical column significantly lower than that indicated in the top horizontal row at specified region. Third and fourth rows indicate the start and end of a region of difference (%). Adjusted alpha value=0.001 (45 comparisons)

C. *Post hoc* comparisons reported alongside individual force traces (confidence intervals omitted for clarity); Lines coloured more darkly in subsequent sets, with grey lines=sets 1–5; Black lines=sets 6-10

Discussion

To the authors' knowledge, this is the first study to characterize the F-T profile of a commonly employed, damaging DJ protocol, including changes between sets, and analysis of a repeated bout. Additionally, this is the first study to investigate the effect of compression worn during recovery on changes in DJ characteristics. Fatigue over successive sets was characterized by reduced jump height and RSI and increased contact/propulsive times, with SPM revealing a progressive decline in initial braking force. Together, these findings suggest that repeated DJs cause neuromuscular fatigue and altered landing mechanics. No differences in the force or velocity of eccentric contraction were observed between bouts, suggesting that the repeated bout of DJs provided an equivalent eccentric stimulus to B1, justifying the use of this protocol in studies investigating RBE. Conversely, force at the start of the propulsive phase declined during B2, whilst propulsive time and peak propulsive force increased. The use of CG for recovery did not influence observed neuromuscular changes between bouts. It is important to note that, although the use of SPM and consideration of complete F-T profiles provides greater context than analysing discrete neuromuscular indices alone, the lack of in-vivo evidence makes it impossible to differentiate physiological changes from alterations in jump strategy. Accordingly, findings will be considered collectively, in the context of existing literature.

In contrast with previous findings [20,21] jump height declined between sets in the current trial. This discrepancy may be explained by the demanding DJ protocol utilized (10x10 DJs from 0.6 m), with papers reporting no fatigue employing DJs from lower heights [19,20], or protocols with fewer jumps [19,21]. Furthermore, whilst previous studies calculated jump height from time in the air, the current study used take-off velocity for greater accuracy [47]. Analysis of the complete force profile supports these findings, with propulsive force (>54% of the time series) shown with SPM to decline in later sets. Conversely, contact/propulsive times increased throughout the DJ protocol as reported previously [48], leading to a drop in RSI (Table 1). Such an increase in jump duration may indicate a strategic change to maintain jump performance [14,17,18]. However, declines in jump height began earlier (from S6) than increases in contact time (S8 only - Table 1). In summary, although the relative contribution of strategic and neuromuscular changes are uncertain, changes in jump height and RSI over the protocol indicate the progression of neuromuscular fatigue.

Several observations from the current study describe changes in landing mechanics with neuromuscular fatigue. Importantly, a reduction in braking force between 17–25% of DJ duration was shown by SPM to occur from S5, suggesting a strategic change to dissipate impact forces

[12,14,17,49]. Indeed, previous research has reported reductions in EMG activity [12,17] and impact force [14] during braking when drop-jumps were performed following damaging exercise, potentially due to participants “softening” their landings. It is also possible that braking force declined from cumulative muscle damage, with EIMD known to induce profound reductions in eccentric strength [50]. In either case, the observed set x bout interaction, whereby F0V increased significantly later in B2 (Figure 2, Table 1) could be taken to indicate a delayed onset of neuromuscular fatigue with RBE. In contrast to previous findings, however [12,14], vertical stiffness increased from S1 to S3 (Table 1). Although this finding may seem at odds with the known effects of fatigue on vertical stiffness in the drop-jump [13,51], this observation is consistent with results from a recent study, in which knee-flexion during the landing from a CMJ was reduced following EIMD [52], resulting in greater vertical stiffness. The authors suggested this represented a protective strategy to moderate muscle lengthening and minimize subsequent damage, and is compatible with the observed tendency for DJ depth to increase over the initial three sets (Figure 2). These findings could also be explained by increased muscular potentiation in response to eccentric exercise [53], with the relative contribution of neuromuscular versus strategic responses unclear. In summary, changes in the F-T profile of the landing phase were observed over multiple sets of DJs, indicating EIMD or alterations in jump strategy with fatigue.

A comparison of F-T profiles between bouts suggests that B1 and B2 were mechanically equivalent during the eccentric phase, with no differences in the force, velocity or depth of eccentric contraction. These findings are important as greater forces, velocities and muscle lengths during eccentric contractions exacerbate EIMD [3-5]. Conversely, B2 was characterized by significantly greater peak propulsive forces. In support of a physiological mechanism, RBE is associated with improved post-exercise maintenance of maximal force generation [29], and jump performance [54], which are thought to be partly mediated by musculotendinous adaptations [31,55]. However, similarly to previous studies [19-21], jump height did not improve in B2 as may be expected from attenuated EIMD [14,56]. Alternatively, these findings may be explained by alterations in jump strategy; a notion supported by observations that the decline in *mean* propulsive force during B2 was accompanied by an increased propulsive duration, as well as a reduction in GRF from 59 to 73%, as shown by SPM. A lower mean force applied over a longer time in B2 would result in the maintenance of impulse, and therefore jump height [13,18]. However, the observation that peak propulsive force increased concomitantly with a decline in average propulsive force could also be explained by a physiological mechanism. Eccentric exercise known to elicit both a shift in subsequent motor-unit recruitment towards oxidative, fatigue-resistant fibres [29,33], as well as improvements in tendon compliance [34], which may reduce the rate of force transfer [57]. Future research on isolated muscle is warranted to quantify the effects of repeated DJs on the structural component of RBE.

The use of compression stockings for recovery did not influence the adaptive changes in DJ performance observed between bouts in the current study. These findings contrast with recent results from our laboratory - the only research to date on CG and RBE - which suggest that compression may blunt RBE for isokinetic performance in the lower limb [28]. However, considering the influence of jump strategy on the F-T metrics investigated [13,14,17,18], as well as the complex, dynamic nature of DJs [13,49], it is perhaps unsurprising that this model may not adequately highlight differences in physiological adaptations. The use of CG for recovery had no effect on the F-T profile of a repeated bout of DJs in non-resistance trained males. More research is required to establish the specific effects of CG in different models of muscular adaptation.

The current study is subject to several limitations. Importantly, it must be acknowledged that the calculation of DJ metrics from impact velocity is subject to inaccuracies from estimating drop height [43]. Although the use of reverse integration [58], or adjusting DJ height *post hoc* by calculating the velocity of the centre of mass during quiet standing [43] may improve accuracy, it was not possible to enforce an adequate stabilization period after every one of 100 fatiguing DJs. Another limitation is that differentiating physiological from strategic adaptations is not possible from the current data. Studies in which a variety of different instructions are given before jumping, or particular restrictions imposed [35,59], as well as designs comparing performance in different movement tasks or with different loads [56,60] may be useful in future to help identify specific neuromuscular changes. Additionally, although heterogeneity arising from sex and prior resistance training was limited by our exclusion criteria, the resulting findings are specific to non-resistance trained males. Despite the inclusion of several competitive athletes, it is therefore impossible to inappropriate our findings to athletic populations [1]. The effect of prior sprints and maximal isokinetic testing [41] on DJ performance is also difficult to difficult to determine, and limits the generalization of our findings. Although our study was informed by a power calculation, the relatively small sample size must also be acknowledged. Furthermore, whilst perceived efficacy did not differ between interventions, this is not a direct measure of belief in blinding and represents a limitation.

The current findings suggest that the eccentric component of a repeated bout of DJs is biomechanically equivalent to the initial bout in non-resistance trained males. This suggests that the protective adaptations to EIMD consistently observed following repeated DJs [6,7,28,29] are indeed mediated by RBE, rather than simply reflecting a change in landing strategy to reduce subsequent damage. As RBE may extend to similar movements that use the same muscle-groups [21,61], it is likely that protection from DJs would extend to many exercises used during physical training (such as squatting and jumping), potentially highlighting a functional role for such protocols in building tolerance to eccentric exercise in non-resistance trained athletes. However, considering the injury risk from this particular protocol [28], and the fact that far less damaging exercise challenges still elicit RBE [21,61], a less intense stimulus would be recommended. The use of CG during recovery did not significantly affect jump parameters in the repeated bout, suggesting that previously observed effects on muscular adaptation [28] do not influence the biomechanical profiles of complex movements. The degree to which these biomechanical observations are explained by changes in strategy compared to physiological adaptations is unclear.

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