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**Robertson, CM, Pullinger, SA, Robinson, WR, Smith, ME, Burniston, JG, Waterhouse, JM and Edwards, BJ**

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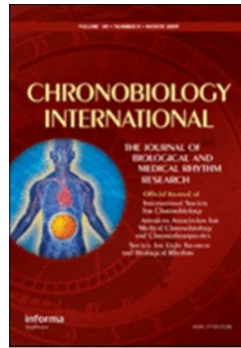
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**Is the diurnal variation in muscle force output detected/detectable when multi-joint movements are analysed using the MuscleLab force-velocity encoder?**

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3 **Is the diurnal variation in muscle force output detected/detectable when multi-joint**  
4 **movements are analysed using the MuscleLab force-velocity encoder?**  
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**ABSTRACT**

We have investigated the magnitude of diurnal variation in back squat and bench press performance using the MuscleLab force velocity transducer. Thirty resistance-trained males (mean  $\pm$  SD: age  $21.7 \pm 1.4$  years; body mass  $80.5 \pm 4.5$  kg; height  $1.79 \pm 0.06$  m) underwent two sessions at different times of day: morning (M, 07:30 h) and evening (E, 17:30 h). Each session included a period when rectal temperature ( $T_{rec}$ ) was measured at rest, a 5-min standardized 150 W warm-up on a cycle ergometer, then defined programme of bench press (at 20, 40 and 60 kg) and back squat (at 30, 50 and 70 kg) exercises. A linear encoder was attached to an Olympic bar used for the exercises and average force (AF), peak velocity (PV) and time to peak velocity (tPV) were measured (MuscleLab software; MuscleLab Technology, Langesund, Norway) during the concentric phase of the movements. Values for  $T_{rec}$  at rest were higher in the evening compared to morning values ( $0.48^{\circ}\text{C}$ ,  $P < 0.0005$ ). Daily variations were apparent for both bench press and back squat performance for AF (1.9 and 2.5 %), PV (8.3 and 12.7 %) and tPV (-16.6 and -9.8 %; where a negative number indicates a decrease in the variable from morning to evening). There was a main effect for load where AF and tPV increased and PV decreased from the lightest load to the heaviest for both bench press and back squat (47.1 and 80.2 %; 31.7 and 57.7 %; -42.1 and -73.9 %;  $P < 0.0005$  where a negative number indicates a decrease in the variable with increasing load). An interaction was found only for tPV, such that the tPV occurs earlier in the evening than the morning at the highest loads (60 and 70 kg) for both bench press and back squat, respectively (mean difference of 0.32 and 0.62 s). In summary, diurnal variation in back squat and bench press was shown; and the time to peak velocity in complex multi-joint movements occurs earlier during the concentric phase of exercise when back squat or bench press is performed in the evening compared to the morning. This difference can be detected using a

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3 low cost, portable and widely available commercial instrument and enables translation of past  
4 laboratory/tightly controlled experimental research in to main-stream coaching practice.  
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## 7 **Introduction**

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9 A large body of laboratory-based research has shown that in male subjects in a temperate  
10 environment (around 17–20°C), muscle power output and force production consistently peak  
11 in the mid-afternoon or early evening. This is regardless of the muscle group measured (such  
12 as hand, elbow, leg, or back) or the speed of contraction (Drust et al. 2005; Reilly &  
13 Waterhouse, 2009). The observation of significant diurnal variation or circadian rhythms in  
14 muscle power and force production seems to be somewhat dependent on factors such as the  
15 time on task, the motivation of subjects to perform and familiarization of the subjects with the  
16 tasks to be performed (Bambaeichi et al. 2003; Giacomoni et al. 2005). Further, it is common  
17 in studies investigating time-of-day variation of muscle force output – for single-joint,  
18 isokinetic and isometric methods to be employed (Callard et al. 2000, Edwards et al. 2013  
19 and Giacomoni et al. 2005). However, the physical demands of sport are such that athletes are  
20 required to move and function in multiple directions, at varying rates of speed and for varying  
21 periods of time. To train these athletes to meet this challenge is typically achieved *via* multi-  
22 directional exercises which are targeted towards enhancing multi-joint and gross muscular  
23 activation (Häkkinen & Komi, 1985). Because of this, strength and conditioning coaches  
24 routinely use multi-joint exercises (back squat and bench press) to monitor and evaluate  
25 muscle force output in a manner which better represents the sporting challenges for which  
26 they are preparing the athlete (Baechle & Earle, 2015).  
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40 Whilst there is convincing evidence to support both time-of-day variation of muscle force  
41 output (Drust et al. 2005; Giacomoni et al. 2005) and the reliability of isokinetic and  
42 isometric maximum voluntary contraction (MVC) methods to measure these differences  
43 accurately (Drouin et al. 2004; Morton et al. 2005). It is yet to be established what tool to use  
44 and if there is a corresponding diurnal fluctuation in complex multi-joint movements that are  
45 more commonly used in applied practice. The ongoing development and validation of a  
46 number of accurate and reliable dynamometers which are able to evaluate dynamic muscle  
47 work have enabled research to be performed within a standardised laboratory environment  
48 with immediately accessible results (Bosco et al. 1995; Jennings et al. 2005; O'Donnell et al.  
49 2017). Taken together with dynamometers being practical, cost-friendly and easy to transport,  
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3 athletes, coaches and sport scientists have taken great interest in using these devices as means  
4 of determining and monitoring athlete performance (Chiu et al. 2003; García-Ramos et al.  
5 2016; Harris et al. 2010). One such device/dynamometer is the MuscleLab linear encoder  
6 system, which measures average force (N), along with peak velocity ( $\text{m}\cdot\text{s}^{-1}$ ) and time to peak  
7 velocity (s), and can be attached to any moving limb or piece of exercise (resistance)  
8 equipment (Bosco et al. 1995). As such, it enables measurement across a broad range of  
9 human functions; as opposed to requiring – or stipulating – what movements are needed in  
10 order to measure such factors. However, to the knowledge of the authors this device has  
11 never been used in a chronobiological research design. Therefore, the aim of this study was to  
12 assess the sensitivity of the MuscleLab force-velocity linear encoder (Ergotest version 4010,  
13 Norway), to determine whether it was able to detect diurnal variation in multi-joint muscle  
14 force output at different masses (low and height) during a bench press (upper body) and back  
15 squat (lower body). We hypothesis that the MuscleLab force-velocity linear encoder is  
16 sensitive to measure diurnal variation in force output in bench press and back squat at  
17 difference masses on the bar.  
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## 29 **Methods**

### 30 **Subjects**

31 Thirty healthy active males (mean  $\pm$  SD: age  $21.7 \pm 1.4$  years; body mass  $80.5 \pm 4.5$  kg;  
32 height  $1.79 \pm 0.06$  m) recruited from Liverpool John Moores University Sports Scholarship  
33 Scheme participated in this study. Verbal explanation of the experimental procedure was  
34 provided to each individual; this included the aims of the study, the possible risks associated  
35 with participation and the experimental procedures to be utilized. Any questions were  
36 answered. Individuals then provided written, informed consent before participating in the  
37 study. The experimental procedures were approved by the Human Ethics Committee at  
38 Liverpool John Moores University. All of the participants used in this study had a minimum  
39 of two-year's experience of resistance training, and were competent in their use of such  
40 equipment and comfortable in this type of training environment. Recruiting participants with  
41 this specific type of exercise history meant that the known neuromuscular facilitative  
42 responses, which are typically associated with acute increases in muscular strength amongst  
43 untrained individuals due to neural adaptations and responses were reduced (Häkkinen,  
44 1989).  
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3 Participants were asked to avoid any strength training during the entire experimental  
4 condition and to avoid taking part in any physical training or hard activity sessions of an  
5 aerobic or anaerobic nature. Participants were also required to avoid all alcohol 24 hours (h)  
6 prior to each test. None of the participants presented with a history of bone fractures and/or a  
7 history of musculoskeletal abnormality; and none of the participants were receiving any  
8 pharmacological treatment during the course of this study. The circadian chronotype of the  
9 participants was assessed using a composite 'morningness questionnaire' by Smith et al.  
10 (1989). The participants' mean 'chronotype' score on a 13 – 52 scale was  $33.1 \pm 5.5$ , hence  
11 all of the participants were 'intermediate types'. A circadian type inventory questionnaire of  
12 Folkard & Monk (1979) determining languidness/vigorous and flexibility/rigidity of  
13 participants was also utilized. The participants' mean scores were  $39.8 \pm 7.2$  and  $45.3 \pm 6.4$   
14 for languidness/ vigour and flexibility/rigidity respectively. Only one of the participants was  
15 found to be flexible and two were found to be languid. All other participants were deemed  
16 rigid and vigorous according to the definitions of the questionnaire. All participants gave  
17 their written informed consent. The study was conducted in accordance with the ethical  
18 standards of the journal and complied with the Declaration of Helsinki.

### 29 **Research design**

30 Each participant first completed familiarisation sessions (detailed below), then the 2  
31 experimental sessions at 07:30 and 17:30 h. These experimental sessions were  
32 counterbalanced in order of administration in order to minimise any potential learning effects  
33 (Monk & Leng, 1982), with a minimum of 72 h to ensure recovery between trials.

### 39 **Protocol: Familiarisation Session**

40 Each participant performed a minimum of four familiarisation sessions under standard  
41 laboratory conditions (lighting = 200-250 lux, temperature = 20-22°C, mean humidity = 50±5  
42 %), conducted over a two-week period and finishing one week before the study commenced  
43 in order to minimize learning effects. The initial familiarisation sessions were used to  
44 determine working loads (mass/resistance) that would be appropriate for the cohort. Each  
45 participant was asked to perform the back squat with incrementing loads (30, 50, 70 and 90  
46 kg) with one repetition at each load, and 5 minute (min) rest was allowed between each  
47 effort. For bench press, each participant performed one repetition against each incrementing  
48 load (20, 40, 60 and 80 kg) and, again, 5-min rest was given between each load. This was  
49 done so that the upper loads required for the experimental trials (back squat, 70 kg; bench  
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3 press, 60 kg) were known to be comfortably within each of the participant's physical  
4 capabilities, and so there was minimal likelihood of their failing to perform the  
5 required efforts for data collection, especially as this trial was not a measure or test of  
6 maximal strength but rather an investigation regarding the components which produce  
7 muscle force output. The familiarisation sessions were allocated in a counterbalanced  
8 fashion, with half of the participants taking part in the morning (at 07:30 h) and the  
9 remaining half during the evening (at 17:30 h), and were separated by at least 3 days,  
10 and each participant did this twice.  
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### 16 17 **Testing Procedure**

18 Participants were required to retire at 22:30 h and rise at 06:30 h; and be in the laboratory 30  
19 min prior to measurements being taken so 07:00 and 17:00 h, respectively. Subjects came  
20 into the morning session having fasted and were not allowed to consume food 4 h before the  
21 evening session. On arrival compliance to the protocols sleeping, food intake and exercise  
22 restrictions were assessed verbally and this was high. Thereafter, rectal temperature (T<sub>rec</sub>)  
23 was measured using a soft flexible rectal probe (Mini-thermistor, Grant Instruments Ltd,  
24 Shepreth, UK) inserted ~10 cm beyond the external anal sphincter. While subjects remained  
25 in a standardised position (semi-supine and awake), T<sub>rec</sub> was recorded continuously for a 30  
26 min period by means of a Squirrel 1000 data logger (Grant Instruments Ltd, Shepreth, UK),  
27 with the average value recorded over the last 5-min being retained for analysis. This standard  
28 body position was used since core body temperature is subject to other influences than that  
29 produced by the endogenous 24 h period oscillator, such as muscle activity, feeding and sleep  
30 (Bougard et al. 2009, Edwards et al. 2002). As with the familiarisation period, all procedures  
31 were conducted under standard laboratory conditions for lighting, humidity and temperature  
32 as previously described. The daily energy intake on test days was controlled and limited to  
33 2500 Kcal, which complies with the British Nutrition Foundation's recommended daily  
34 calorific intake for a mature man ([www.nutrition.org.uk/home.asp](http://www.nutrition.org.uk/home.asp), accessed on 17.04.2018).  
35 Water and non-caffeinated/non-alcoholic, calorie-free beverages were allowed ad libitum up  
36 to a total volume of 3 L per day.  
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51 Participants were required to perform a standardized 5-min warm-up on a cycle ergometer  
52 (Monark 817E, Stockholm, Sweden) at 150 W. Following the warm-up procedure, the  
53 methods for assessing muscle force output were performed (See Figure 1).  
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3 \*\*\*\*Insert Figure 1 near here\*\*\*\*  
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6 **Back Squat and Bench Press** (*MuscleLab, Ergotest version 4010, Norway*)

7 The decision not to employ one-repetition-maximum (1RM) testing in this present study was  
8 largely due to the varying nature of the elite athletic disciplines the participants came from,  
9 and that as Buckner et al. (2017) report the 1RM is a specific skill which warrants specific  
10 training, and therefore favours those with experience of using it in training. Whilst muscle  
11 strength is commonly measured *via* the performance of a one-repetition maximum (1RM)  
12 protocol, Buckner et al. (2017) state that a true measurement of strength remains tenuous with  
13 this approach. Further, that low-load alternatives to traditional resistance training result in  
14 muscle hypertrophic changes similar to those resulting from traditional high-load resistance  
15 training, but with less robust changes observed with maximal strength as measured by the  
16 1RM. For this present study, each of the participants performed the two exercises in a  
17 randomised order, performing either back squat or bench press (or vice versa), performing  
18 three lifts at each exercise against progressively increasing loads (bench press: 20, 40 and 60  
19 kg; back squat 30, 50 and 70 kg), with 5-min rest allowed between each lift (See Figure 1).  
20 There is evidence to suggest that the optimal training load for performance enhancement is  
21 one that emphasizes the athlete's maximum power output (Ammar et al. 2018, Comfort et al.  
22 2011), in bench press and squat exercise, with moderate loads (from >30 to <70 % of 1RM)  
23 appearing to provide the ideal load for power production. However, in line with  
24 recommendations provided by Buckner et al. (2017), and the findings of Pareja-Blanco et al.  
25 (2016), the present study utilised loads above 80 % of those measured as a better indication  
26 of strength ability, and therefore prompting a maximal effort. The upper values here (bench  
27 press: 60 kg, and back squat: 70 kg) equate to 85 % (bench press) and 80% (back squat) of  
28 the upper load achieved during the familiarisation phase. As such, the participants were  
29 performing outside of the loading realms of a routine training stimulus, and confidently  
30 within a maximal loading/effort range. The individual's own body mass was factored into the  
31 back squat exercise, as this is a whole-body movement, but not into the bench press. The  
32 MuscleLab force-velocity linear encoder was attached to an Eleiko Olympic bar (20 kg)  
33 which was set upon rests within a standard squat rack so that the participant had a 90° knee  
34 flexion position (settings measured and recorded during the familiarisation process). From  
35 this position, the participant was instructed to drive the bar upwards as forcefully as possible;  
36 the value recorded during the test was for the concentric phase of the action only. The  
37 MuscleLab system measured both the average force produced, the peak velocity and time-to-  
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3 peak velocity for each individual lift. This process was repeated three times, with 5-min rest  
4 allowed between each individual lift, and against the progressive workloads as described  
5 above. For the bench press, the bar was set so that it rested just above (~2.5 cm) the  
6 participant's chest and, again, the instruction given was to push against the bar as forcefully  
7 as possible. Again, this was repeated three times against the workloads described above, with  
8 5-min rest between each push. The highest of the three average force outputs (and associated  
9 peak velocity and time to peak velocity values) were used for analysis for each mass on the  
10 bar for both bench press and back squat respectively. Only the lower and highest loads of the  
11 back squat and bench tests were analysed. This was to allow the participant to perform at  
12 greater velocities (lowest load) and challenging overall muscle force output when the ability  
13 to move quickly has been reduced (at the highest loads). The middle load was used purely for  
14 the purpose of preparing the participant within the trial for the incremental increase in  
15 demand, to both reduce the potential for injury and to allow them to adjust more  
16 progressively to an increase external load. In order to reduce the likelihood of injury, two  
17 people were positioned either side of the participants as they performed their lifts, to  
18 intervene if there was a problem. In addition, there were safety supports in place on every  
19 occasion (so that, if any participant had to release the weight for any reason, it would not fall  
20 upon them).

### 31 32 33 **Statistical analysis**

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35 The Statistical Package for the Social Sciences (SPSS), version 22, for Windows were used.  
36 All data were checked for normality using the Shapiro-Wilk test. Differences between  
37 conditions were evaluated using a general linear model with repeated measures, within  
38 subject factor 'time of day' (2 levels) and within subject factor 'load on bar' (2 levels) and  
39 interaction. To correct violations of sphericity, the degrees of freedom were corrected in a  
40 normal way, using Huynh-Feldt ( $\epsilon > 0.75$ ) or Greenhouse-Geisser ( $\epsilon < 0.75$ ) values for  $\epsilon$ , as  
41 appropriate. Graphical comparisons between means and Bonferroni pairwise comparisons  
42 were made where main effects were present. Only the data obtained from the first and final  
43 lifts of the back squat and bench tests were analysed, as they represent the two extremities of  
44 the force-velocity relationship; lesser resistances typically allowing for greater peak velocities  
45 and greater resistances usually leading to larger average force values. The  $\alpha$ -level of  
46 statistical significance was set at  $P < 0.05$ , and values of '0.000' given by the statistics  
47 package are shown here as  $P < 0.0005$  (Kinear & Gray, 1995). Effect sizes (ES) were  
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3 calculated from the ratio of the mean difference to the pooled standard deviation. The  
4 magnitude of the ES was classified as trivial ( $\leq 0.2$ ), small ( $> 0.2-0.6$ ), moderate ( $> 0.6-1.2$ ),  
5 large ( $> 1.2-2.0$ ) and very large ( $> 2.0$ ) based on guidelines from Batterham & Hopkins  
6 (2006). The results are presented as the mean  $\pm$  the standard deviation throughout the text  
7 unless otherwise stated. Ninety-five percent confidence intervals are presented where  
8 appropriate.

## 11 **Results**

### 12 *Resting rectal temperature*

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14 There was a significant time-of-day difference with higher resting  $T_{rec}$  values in the E (mean  
15 difference =  $0.49^{\circ}\text{C}$ ,  $P < 0.0005$ , 95 % CI:  $0.34-0.64^{\circ}\text{C}$ ; ES=1.36) compared to the M  
16 condition (See Table 1).  
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21 \*\*\*\*Insert Table 1 and Figure 2 near here\*\*\*\*

### 22 *Muscle Strength Measurements*

#### 23 **Bench press**

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25 Daily variations were apparent for the bench press for AF, PV and tPV (See Table 1). Where  
26 AF (mean difference of two loads =  $10.8\text{ N}$ ,  $P < 0.0005$ , 95 % CI:  $6.4-15.3\text{ N}$ ; ES=0.21), and  
27 PV values were higher in the evening than the morning (mean difference of two loads =  $0.13$   
28  $\text{ms}^{-1}$ ,  $P < 0.0005$ , 95 % CI:  $0.08-0.19\text{ ms}^{-1}$ ; ES=0.52). And tPV values occurred earlier in the  
29 evening than the morning (mean difference of two loads =  $0.12\text{ s}$ ,  $P = 0.001$ , 95 % CI:  $0.07-$   
30  $0.18\text{ s}$ ; ES=0.45). There was a main effect for load ( $P < 0.05$ ) such that for AF (mean  
31 difference =  $363\text{ N}$ ,  $P = 0.001$ , 95 % CI:  $357-369\text{ N}$ ), and tPV (mean difference =  $0.62\text{ s}$ ,  $P <$   
32  $0.0005$ , 95 % CI:  $0.45-0.78\text{ s}$ ) values were higher at greater masses on the bar than lower  
33 ones. And PV (mean difference =  $1.09\text{ ms}^{-1}$ ,  $P = 0.001$ , 95 % CI:  $0.95-1.22\text{ ms}^{-1}$ ; See Table 1)  
34 values were lower with higher masses. There was a significant interaction for tPV such that  
35 the time to peak velocity occurred earlier in the evening than the morning for the highest load  
36 (mean difference of  $0.62\text{ s}$ ,  $P = 0.006$ ; See Figure 2 and Table 1).  
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#### 46 **Back squat**

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48 Daily variations were apparent for the back squat for AF, PV and tPV (See Table 1). Where  
49 AF (mean difference of two loads =  $27.6\text{ N}$ ,  $P < 0.0005$ , 95 % CI:  $17.7-37.5\text{ N}$ ; ES=0.18),  
50 and PV values were higher in the evening than the morning (mean difference of two loads =  
51  $0.13\text{ ms}^{-1}$ ,  $P < 0.0005$ , 95 % CI:  $0.08-0.17\text{ ms}^{-1}$ ; ES=0.51). And tPV values occurred earlier  
52 in the evening than the morning (mean difference of two loads =  $0.07\text{ s}$ ,  $P = 0.001$ , 95 % CI:  
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0.04-0.10 s; ES=0.31). There was a main effect for load ( $P < 0.05$ ) such that for AF (mean difference = 330 N,  $P = 0.001$ , 95 % CI: 320-340 N), and tPV (mean difference = 0.32 s,  $P < 0.0005$ , 95 % CI: 0.25-0.39 s) values were higher at greater masses on the bar than lower ones. And PV (mean difference = 0.48  $\text{ms}^{-1}$ ,  $P < 0.0005$ , 95 % CI: 0.37-0.59  $\text{ms}^{-1}$ ) See Table 1) values were lower with heavier masses. There was a significant interaction for tPV such that the time to peak velocity occurred earlier in the evening than the morning for the highest load (mean difference of 0.32 s,  $P = 0.001$  See Figure 2 and Table 1).

## Discussion

We report the MuscleLab linear encoder (Ergotest, version 4010, Norway) is capable of detecting a diurnal variation in muscle force output when used with back squat and bench press (multi-joint) exercises. More importantly, this piece of apparatus is able to detect this fluctuation for the three dimensions of muscle force output: average force, peak velocity and time to peak velocity. Where average force and peak velocity increased from morning to evening by 2.5, 12.7 % and time to peak velocity decreased by 16.6 %, for bench press (for 20 and 60 kg). And, similarly average force and peak velocity increased from morning to evening by 1.9, 8.3 % and time to peak velocity decreased by 9.8 %, for back squat (for 30 and 70 kg). Further, a diurnal variation in resting rectal temperature of 0.49°C was found, a difference previously reported. Taken together these findings are in agreement with existing literature regarding time-of-day variation in rectal temperature and muscle force output (See Edwards et al. 2013), which has consistently demonstrated that the highest values of muscle force output coincide with the daily peak of the rhythm for core temperature (15:00–18:00 h; Reilly & Waterhouse, 2009) and the least values with the lowest core temperatures (03:00–06:00 h).

A main effect for 'load' was also found as expected, for both bench press and back squat, where average force and time to peak velocity increased and peak velocity decreased, from lower to higher loads on the bar (47.1 and 80.2 %; 31.7 and 57.7 %; -42.1 and -73.9 %;  $P < 0.0005$  where a negative number indicates a decrease in the variable with increasing load). That force production increases with increasing load, agrees with other authors who have used different methodology's such as equipment (force platforms and motion capture systems) and strength techniques (power clean, hang clean and hang power clean; Ammar et al. 2018). This is a typical relationship in terms of the production of overall power; as the external load increases, the rate ( $\text{ms}^{-1}$ ) at which the movement is achieved is inhibited by the

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3 greater mass. As such, the strength (force output/power) component of the power equation  
4 (power = force x speed) is the primary influence of the increase 'load' we have observed  
5 during the evening. In the present study, only the data obtained from the first and final lifts of  
6 the back squat and bench tests were analysed. The lower resistance (mass on bar) creates an  
7 opportunity for the participant to perform at greater velocities, whilst the greater resistance  
8 will ascertain a difference in overall muscle force output when the ability to move quickly  
9 has been reduced. Essentially, they represent the two extremities of the force-velocity  
10 relationship, lesser resistances typically allowing for greater peak velocities and greater  
11 resistances commonly leading to larger average force values.  
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19 A main finding of the current study was that an interaction was found for time of day and  
20 load on the bar. Such that participants could achieve maximal rates of velocity in less time  
21 during the heavier lifts, in both lower and upper body exercise in the evening. Although, the  
22 mechanisms regarding development of RFD remain largely unknown (Rodriguez-Rossell et  
23 al. 2017), this evening superiority in rate of force development (RFD) provides an insight as  
24 to how greater peak velocities and power outputs in the evening are achieved. This time of  
25 day effect on RFD may be linked with a selective effect on fast twitch protein isoforms (e.g.  
26 IIA or x myosin heavy chain profile) or on the processes of excitation contraction coupling.  
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34 At present, the exact mechanisms for the observed diurnal variation in muscle performance  
35 are unknown. We have covered this previously (Edwards et al. 2013) but in brief it has been  
36 attributed to **i)** input from the body clock and proteins and peripheral clocks - that is, an  
37 endogenous component to the daily variation in muscle force production - has been suggested  
38 to be important (Zhang et al. 2009). The evidence relating to this is limited. **ii)** The causal  
39 link between core temperature and performance has been investigated, although this has been  
40 shown to be complex, due to a multiplicity of components and mechanisms which require  
41 further research (Edwards et al. 2013). Further, **iii)** peripheral or muscle-related variables  
42 (contractility – time to peak velocity in agreement with the current study's  
43 findings, metabolism, morphology of muscle fibres, accrued damage during exercise and  
44 local muscle temperature), which can be influenced by hormonal and ionic muscle  
45 process variations (Reilly & Waterhouse, 2009; Tamm et al. 2009), and/or **iv)** central/  
46 neurological factors (central nervous system command, alertness, motivation, and mood;  
47 Castaingts et al. 2004; Giacomoni et al. 2005; Racinais et al. 2005a, 2010) have been  
48 suggested.  
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3 To the best of our knowledge, this is the first study using linear encoder technology in a  
4 chronobiological research design. We have duplicated time of day and muscle force and  
5 power findings previously reported in only laboratory based strength assessment (such as  
6 isokinetic and isometric methods); but used complex exercises that better replicate the  
7 movements associated with athletic performance (Chapman et al. 1998, LeSuer et al. 1997).  
8 In the case of the lower limbs the back squat and in the case of the upper limbs/torso the  
9 bench press. Power output is arguably the primary determinant of sport success; however  
10 RFD is also important on its own and can be considered an underpinning mechanism of  
11 power output (Bevan et al. 2010; Hawley et al. 1992; Stone et al. 2002, Taber et al. 2016).  
12 The findings presented in this study are, therefore, of far greater relevance to athletic  
13 performance that previously research in this area and provide an ecologically meaningful  
14 assessment of the vital physical qualities (particularly rate of force development) that  
15 contribute towards sport performance allowing previously published laboratory based and  
16 tightly controlled experimental research to be readily translated into main-stream coaching  
17 practice. In the case of the current study's findings have implications for training RFD in  
18 evening and impact on sporting performance.  
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30 Lastly, effective managing, planning, periodization and phase potentiation of the specific  
31 component parts of muscle force output is essential for optimal training (DeWeese et al.  
32 2015). The linear encoder equipment lends itself for this use, as well as measurement of  
33 adaption during micro- and mesocycles and providing real time information to submaximal  
34 and one-repetition maximum tests (1 RM). The Linear encoder system can fit to any  
35 traditional gym based equipment for specificity assessment, hence giving the researcher or  
36 practitioner freedom of choice to choose exercises that employ the required sports-specific  
37 technical abilities and important skills being developed an investigated; whilst also providing  
38 insights and relationships of average force, peak velocity and time to peak velocity of specific  
39 muscle force output. Unlike the traditional approaches of muscle assessment such as Wingate  
40 anaerobic power test, force plate (for RFD) and/ or isokinetic or isometric dynamometry which  
41 limit the range and type of movements being assessed and measurement of single muscles  
42 might (as in the instance of isokinetic dynamometry) mask the force output of a group of  
43 muscles (Chtourou et al. 2011, Souissi et al. 2010).  
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#### 54 **Limitations**

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3 We have shown clear diurnal variation for muscle performance using the linear encoder but  
4 further work should extend this to a 24 h period allowing circadian characteristics to be  
5 determined (such as mesor, acrophase and amplitude), but also using protocols where in the  
6 endogenous component to performance can be elicited (either using a constant routine or  
7 ultra-short wake-cycle experimental design). In the current study we measured only  
8 resting rectal temperature, future work should measure pre and post exercise rectal and  
9 muscle temperature to better explore the core and muscle temperature causal link  
10 with gross muscular performance (See Edwards et al. 2013 and Pullinger et al. 2018). In  
11 our study, we recruited intermediate chronotypes, future work could investigate the  
12 sensitivity of linear encoders to find a diurnal variation for muscle performance using  
13 outright morning or evening types.  
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## 22 **Summary**

23 The MuscleLab linear encoder provides a suitable tool for measuring diurnal variations in  
24 muscle force output on multi-joint movements which more closely resemble athletic  
25 performance. The advantages of this approach allow the time-of-day variation in muscle  
26 force output to be measured in complex multi-joint human movements, over an array of  
27 submaximal to maximal loads rather than isolated single joint maximal efforts.  
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## 35 **Acknowledgements**

36 We would like to thank the participants who participated in the study. We would also like to  
37 acknowledge the intellectual input of Professor James M. Waterhouse who sadly passed away  
38 in October 2016.  
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## 45 **Declaration of interest**

46 The authors report no conflicts of interest, the linear encoder was bought from internal funds  
47 and there is no link between our laboratory and chronobiology group and the MuscleLab  
48 Company. The authors are responsible for the content and writing of this article.  
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## 54 **Practical implications**

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3 The present study supports the established notion of an evening preference (or optimal time  
4 of day) for strength training, but due to the diurnal nature of the current investigation it is not  
5 possible to quantify how much of this is due to the endogenous component of circadian  
6 rhythmicity. That said, as the majority of athletes will live and train in typical diurnal  
7 conditions such that they sleep at night and wake and are active in the day time, the findings  
8 of this study support the idea strength training should be undertaken in the early to late  
9 evening (17:00 to 19:00 h). Specifically where maximal or near-maximal external loads are  
10 involved or a requirement for producing peak velocity outputs (explosive power work,  
11 sprinting, or plyometric training for example).  
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19 Participants could achieve maximal rates of velocity in less time during the heavier lifts in  
20 both lower and upper body exercise in the evening. Although the mechanisms regarding  
21 development of RFD remain largely unknown (Rodriguez-Rossell et al. 2017), this evening  
22 superiority in rate of force development (RFD) provides an insight as to how greater peak  
23 velocities and power outputs in the evening are achieved. Research investigating the potential  
24 time of day specificity to training as previously attempted by other authors (such as Sedliak et  
25 al. 2008), but now employing linear encoders (measuring muscle force output, RFD and peak  
26 velocity) and conducting upper and lower body tasks such as in this study are warranted.  
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34 Past laboratory based and tightly controlled experimental research can now be translated into  
35 main-stream coaching practice. New and emerging intervention and methods that look to use  
36 either chronobiotics such as bright light or exercise, to directly shift the body clock or dawn  
37 simulators to improve mood (Thompson et al. 2014) or investigate the causal relationship  
38 between performance and Trec or muscle temperature – to ultimately increase morning gross  
39 muscular performance and aid athletes that have to compete or undergo training in the  
40 morning could be tested in a real world context using MuscleLab (linear encoder).  
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## List of Figures and Tables

**Figure 1:** Schematic of the protocol for the morning (M 07:30 h) and evening (E, 17:30 h) conditions. Rectal (T<sub>rec</sub>) temperature was measured after the subjects had reclined for 30 min at the start of the protocol (solid black box). Average force, peak velocity and time to peak velocity were measured three times for each weight (black lines), for bench press and back squat respectively. There was 5-min recovery time for each lift.

**Figure 2:** Mean and 95 % confidence intervals (corrected for between-subject variability) for average force, peak velocity and time to peak velocity for Bench Press (for 20 and 60 kg) and Back Squat (for 30 and 70 kg) respectively at 07:30 and 17:30 h. # indicates a time of day effect; + indicates a load effect; \* indicates interaction between 'load' and 'time of day'.

**Table 1:** Mean ( $\pm$  SD) values for rectal temperature, bench press and back squat for morning (07:30 h) and evening (17:30 h) conditions. Where only a *P*-value for time of day is given this indicates a paired *t*-test has been undertaken to remove load and interaction effects. Statistical significance ( $P < 0.05$ ) is indicated in bold.

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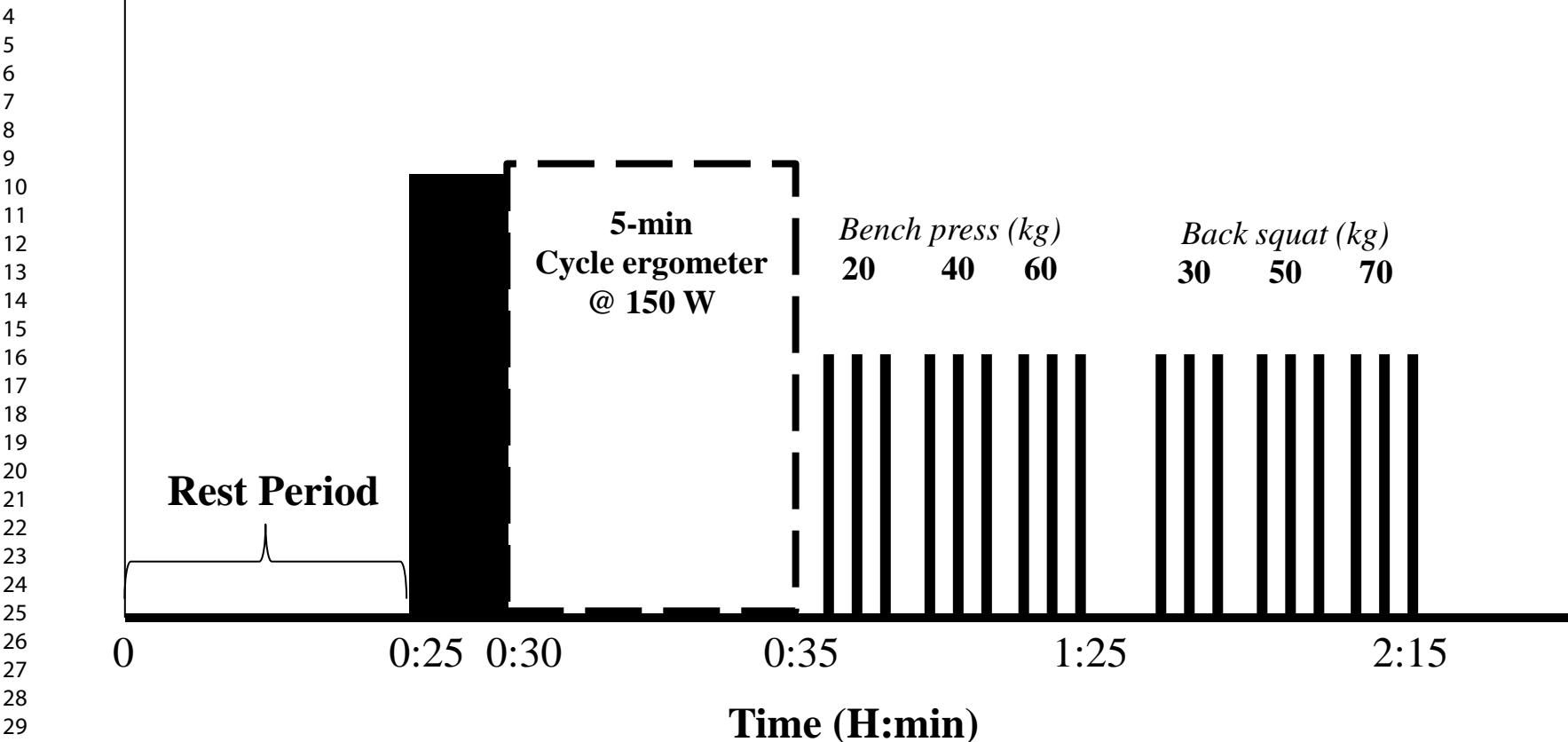
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1 *Insert probe*  
2 *and lay down*  
3



32 **Figure 1.**



### Bench press

### Back squat

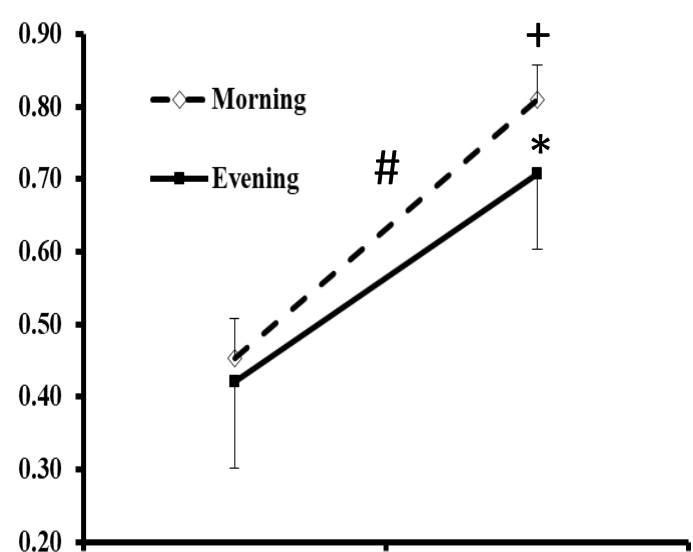
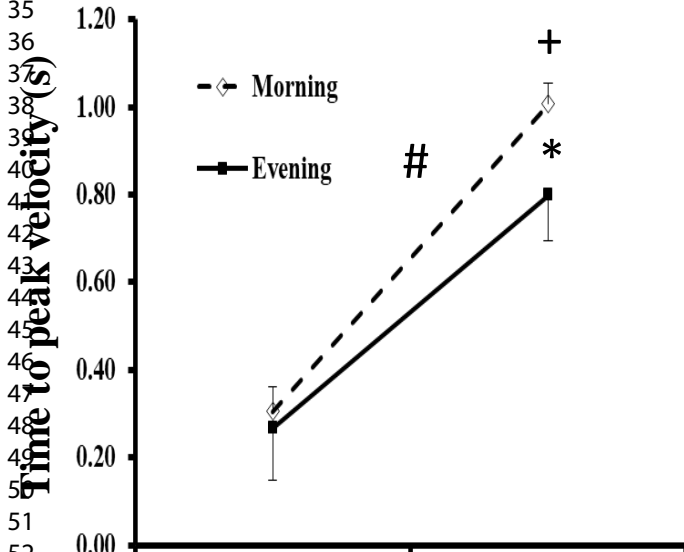
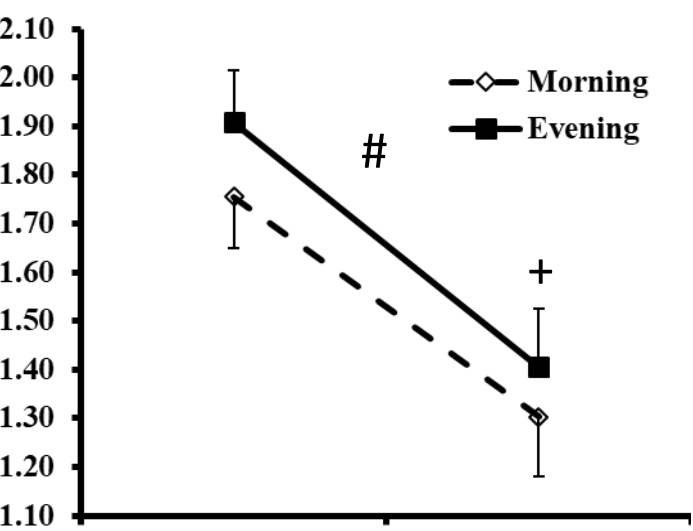
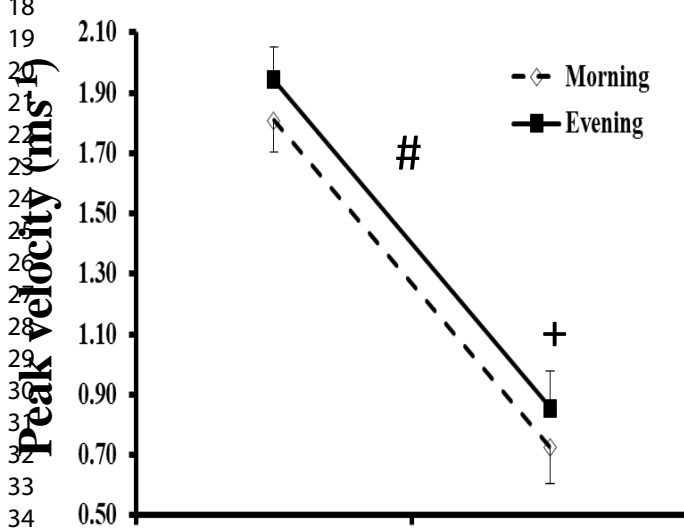
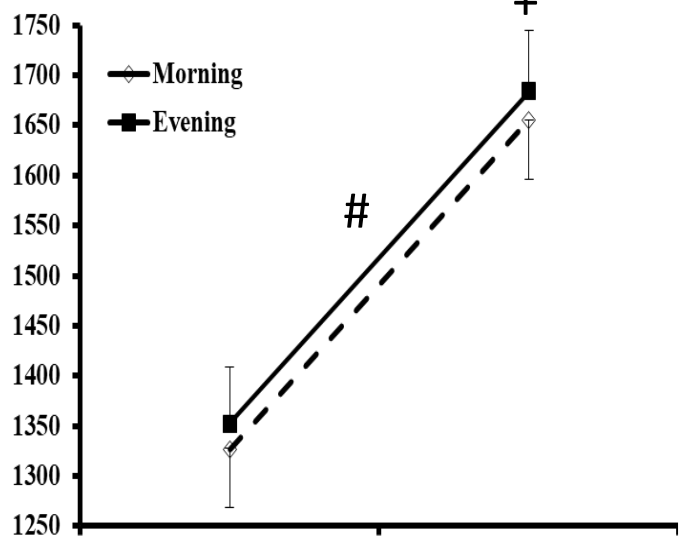
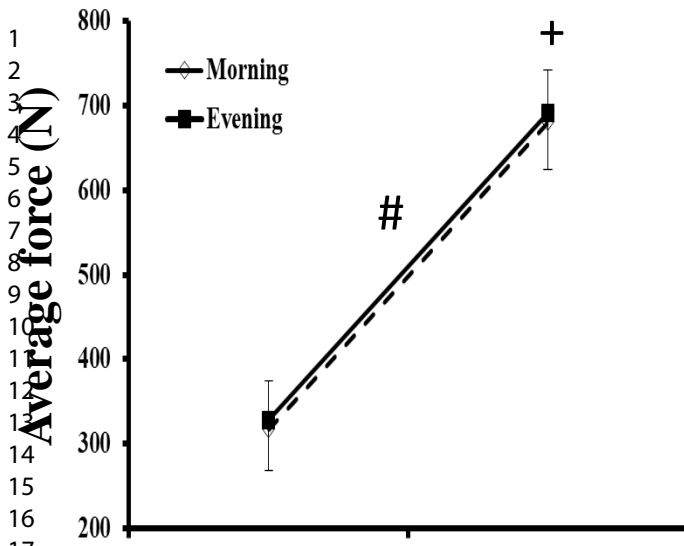


Table 1

Measure	Variable	Morning (M)	Evening (E)	<i>P</i> -value Time of day
<b>Resting Rectal temperature</b>	Trec (°C)	36.5 ± 0.3	37.0 ± 0.4	<0.0005
<b>Bench Press</b>				
20 kg	AF (N)	317.3 ± 46.5	328.3 ± 48.6	= 0.0004
	PV (ms <sup>-1</sup> )	1.81 ± 0.34	1.94 ± 0.35	= 0.002
	TpV (s)	0.31 ± 0.07	0.27 ± 0.07	< 0.0005
60 kg	AF (N)	680.5 ± 51.1	691.1 ± 56.5	< 0.0005
	PV (ms <sup>-1</sup> )	0.73 ± 0.26	0.86 ± 0.34	< 0.0005
	TpV (s)	1.01 ± 0.58	0.80 ± 0.43	< 0.0005
<b>Back Squat</b>				
30 kg	AF (N)	1326.3 ± 150.4	1352.4 ± 162.0	= 0.0002
	PV (ms <sup>-1</sup> )	1.76 ± 0.28	1.91 ± 0.32	= 0.0002
	TpV (s)	0.45 ± 0.15	0.42 ± 0.13	= 0.011
70 kg	AF (N)	1654.9 ± 156.2	1683.9 ± 155.7	< 0.0005
	PV (ms <sup>-1</sup> )	1.30 ± 0.29	1.41 ± 0.30	< 0.0005
	TpV (s)	0.81 ± 0.32	0.71 ± 0.28	< 0.0005