A low caffeine dose improves maximal strength, but not relative muscular endurance in either heavier- or lighter-loads, or perceptions of effort or discomfort at task failure in females

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Background. The body of literature considering caffeine as an ergogenic aid has primarily considered typically aerobic based exercise, male participants and moderate- to large-caffeine doses. With this in mind the aim of this project was to explore the effects of a low-caffeine dose upon maximal voluntary contraction (MVC), and muscular endurance (time to task failure; TTF) at heavier- and lighter-loads. **Methods**. Nineteen physically active, habitual caffeine consuming females randomly performed 4 testing conditions; 2 with a low-dose of caffeine (100mg equating to mean = 1.5 ±0.18mg.kg^{-1}) and 2 placebo conditions, where they performed a maximal strength test (MVC) knee extension at 45° followed by a task of relative muscular endurance (sustained isometric contraction for time to task failure; TTF) using either heavier- (70% MVC) and lighter- (30% MVC) loads. Each participant performed each load condition following both caffeine and placebo consumption. Immediately following cessation of the muscular endurance test participants were asked to report their rating of perceived effort (RPE) and rating of perceived discomfort (RPD). **Results**. Analyses revealed a significant effect for caffeine upon MVC compared to placebo (p=0.007). We also found a significantly greater TTF for the lighter- compared to the heavier-load condition (p<0.0001); however, there was no significant effect comparing caffeine to placebo (p=0.2368), but insufficient precision of estimates to infer equivalence in either lighter- (p=0.750) or heavier-load (p=0.262) conditions. There were no statistically significant effects for caffeine compared with placebo, or lighter- compared with heavier-loads, for RPE and RPD (all p>0.05). RPE was statistically equivalent between caffeine and placebo for both lighter- (p=0.007) and heavier-load (p=0.002) conditions and RPD for heavier- (p=0.006) but not lighter-load (p=0.136). **Discussion**. This is the first study to demonstrate a positive effect on strength from a low caffeine dose in female participants. However, it is unclear whether caffeine positively

impacts upon relative muscular endurance in either heavier- or lighter-loads. Further, both RPE and RPD appear to be relatively similar during isometric tasks performed to task failure independently of caffeine supplementation or load. These findings may have implications for persons wishing to avoid side-effects or withdrawal symptoms associated with larger caffeine doses whilst still attaining the positive strength responses.

1 A low caffeine dose improves maximal strength, but not relative muscular endurance in either heavier- or lighter-

2 loads, or perceptions of effort or discomfort at task failure in females

4 Running Title: Low caffeine dose improves strength in females

6 Original Research Article

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28   project was to explore the effects of a low-caffeine dose upon maximal voluntary contraction (MVC), and muscular

29   endurance (time to task failure; TTF) at heavier- and lighter-loads.

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31   conditions; 2 with a low-dose of caffeine (100mg equating to mean = 1.5 ±0.18mg.kg^{-1}) and 2 placebo conditions,

32   where they performed a maximal strength test (MVC) knee extension at 45° followed by a task of relative muscular

33   endurance (sustained isometric contraction for time to task failure; TTF) using either heavier- (70% MVC) and

34   lighter- (30% MVC) loads. Each participant performed each load condition following both caffeine and placebo

35   consumption. Immediately following cessation of the muscular endurance test participants were asked to report

36   their rating of perceived effort (RPE) and rating of perceived discomfort (RPD).

37   **Results**. Analyses revealed a significant effect for caffeine upon MVC compared to placebo (p=0.007). We also

38   found a significantly greater TTF for the lighter- compared to the heavier-load condition (p<0.0001); however,

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40   infer equivalence in either lighter- (p=0.750) or heavier-load (p=0.262) conditions. There were no statistically

41   significant effects for caffeine compared with placebo, or lighter- compared with heavier-loads, for RPE and RPD

42   (all p>0.05). RPE was statistically equivalent between caffeine and placebo for both lighter- (p=0.007) and heavier-

43   load (p=0.002) conditions and RPD for heavier- (p=0.006) but not lighter-load (p=0.136).

44   **Discussion**. This is the first study to demonstrate a positive effect on strength from a low caffeine dose in female

45   participants. However, it is unclear whether caffeine positively impacts upon relative muscular endurance in either

46   heavier- or lighter-loads. Further, both RPE and RPD appear to be relatively similar during isometric tasks

47   performed to task failure independently of caffeine supplementation or load. These findings may have implications

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49   attaining the positive strength responses.

50 **Key words**: strength, maximal voluntary contraction, isometric, discomfort, effort, ergogenic

51 **Introduction**

52   Caffeine is evidenced to increase productivity, improve concentration, and reduce fatigue (Bazzucchi et al.

53 2011; Pickering and Kiely, 2018) and as such, in an effort to enhance performance, it is reported that ~74% of

54 athletes consume caffeine as an ergogenic aid prior to competition (Del Coso et al. 2011). Historically the body of

55 research has considered the effects of caffeine upon predominantly aerobic endurance type exercise, for example;

56 time to exhaustion in well-trained and elite cyclists (Costill et al. 1978, Pasman et al. 1995), 2000m rowing

57 performance (Bruce et al. 2000), and 1500m treadmill running (Wiles et al. 1992). Indeed, a recent umbrella review

58 of published meta-analyses considering the effects of caffeine supplementation on a range of performance

59 outcomes found that evidence was stronger for predominantly aerobic vs. anaerobic tasks (Grgic et al. 2019a). Yet,

60 perhaps in part due to the popularity of caffeinated supplements aimed to harness its aforementioned benefits,

61 caffeine is commonly consumed as part of a 'pre-workout' with the desire to enhance strength, power and

62 muscular endurance before partaking in resistance exercise or strength/power-based tasks (Cesareo et al. 2019). In

63 comparison with aerobic endurance tasks, there is still a gap within the present body of literature considering

64 caffeine consumption and muscular strength/endurance tasks. Further, as with most resistance training studies,

65 the body of research considering the maximal strength and muscular endurance effects of caffeine have

66 dominantly considered trained or untrained male participants.

67   Indeed, a recommendation from recent reviews by Grgic et al. (2019a;2019b) was for more research to be

68 conducted in women. This is supported by evidence suggesting sex-differences in subjective and physiological

69 responses to caffeine consumption (Temple and Ziegler 2011). To date research considering female participants

70 has used large caffeine doses. For example, Goldstein et al. (2010) considered 15 females, reporting a small yet

71 significantly ($p<0.05$) greater barbell bench press 1RM for caffeine (6mg·kg^{-1}) compared to placebo conditions (52.9

72 ±11.1 kg vs. 52.1 ±11.7 kg, respectively). And Sabblah et al. (2015), who compared caffeine (5mg·kg^{-1}) and placebo

73 for strength differences between males (n=10) and females (n=8). The authors reported significantly greater 1RM

74 bench press following caffeine compared to placebo, (p=0.016; males = 101.5 ±28.9 to 107.5 ±30.5kg, females =

75 32.2± 9.0 to 35.3± 7.3kg) with no between sex differences. In addition, they reported a tendency for an increase in

76   relative muscular endurance (repetitions at 40% 1RM; p=0.059) with a between sex difference of p=0.061 in favour

77   of males compared to females as a result of caffeine ingestion. Finally, Sabblah et al. (2015) found no improvement

78   in squat 1RM for either males or females for the caffeine condition. The lack of research considering female

79   participants might simply be a reflection that the bulk of strength training research considers male participants.

80   However, it might also be a product of the sensitivity around female menstrual cycles and oral contraceptive use

81   which might impact the effects of caffeine upon the body (Abernethy and Todd 1985).

82   A further limitation of present literature is a lack of investigation into low caffeine dosage (<3mg·kg^{-1}) for

83   strength measures (Spriet 2014). Indeed, Grgic et al. (2019a) note that the doses of caffeine across the body of

84   literature have generally been around 6mg of caffeine per kilogram of body mass (mg.kg^{-1}) or greater. Some

85   studies suggest that lower doses of caffeine could be impactful upon strength performance. For example, Arazi et

86   al. (2016) reported maximal strength (leg press 1RM) across 2 caffeine conditions (2mg.kg^{-1} and 5mg.kg^{-1}) as well

87   as a placebo condition. Whilst the analyses didn't reveal a statistically significant difference, their descriptive data

88   (leg press 1RM; placebo =154 ±27.3kg vs. 2mg.kg^{-1} of caffeine =171 ±15.9kg) seems noteworthy. A more recent

89   study of the dose-response effects of 2mg.kg^{-1}, 4mg.kg^{-1-}, and 6mg.kg^{-1} of caffeine upon both upper and lower

90   body strength and relative muscular endurance in males reported a linear trend for upper body strength, but no

91   clear dose-response relationship for lower body strength or relative muscular endurance (Grgic et al. 2019c). Thus,

92   there is the possibility that low doses of caffeine may still produce performance enhancing effects. This might be

93   particularly important considering studies reporting negative side effects to caffeine supplementation. For

94   instance, Goldstein et al. (2010) reported that 20% of participants *"exhibited intense emotional side effects,*

95   *including an expressed inability to verbally communicate, focus, and/or remain still as well as the feeling of wanting*

96   *to cry"* (page 4). Other studies have negative side-effects following caffeine withdrawal, including severe fatigue,

97   increased muscle pain and cramps, sleep disturbance, irritability, headaches, and occasional nausea (Nehlig 1999;

98   Juliano and Griffiths 2004). In review, withdrawal symptoms were evident from a median dose of 357mg (in a 60kg

99   female and 80kg male this equates to 5.95mg·kg^{-1} and 4.46mg·kg^{-1}, respectively) but also in doses as low as 129mg

100   (in the same example: 2.15mg·kg^{-1} and 1.61mg·kg^{-1}, respectively; Strain et al. 1994).

101   Finally, an additional gap within the body of research is that to date no empirical publications have

102   considered the impacts of caffeine supplementation upon the effects of heavier- compared with lighter-load

103   muscular endurance tasks. These might differ following caffeine consumption as a result of the effects of caffeine

104   on the neurological system and the potentiation of force production during submaximal intensities (Tarnopolsky

105   2008), as well as the potentially differing effects of caffeine on slow twitch muscle fibres (Davis and Green 2009).

106   Current research suggests that lighter-load resistance exercise tasks, whilst producing similar perceptions of effort

107   at momentary task failure, produce greater discomfort compared to heavier loads (e.g. Fisher and Steele 2017;

108   Stuart et al. 2018). However, these studies did not consider the use of caffeine ingestion which might improve

109   endurance performance through a reduction in perceived effort at submaximal exercise intensities thus deterring

110   task disengagement due to maximal perceived effort for longer (Duncan et al. 2013; de Morree et al. 2014;

111   Smirnaul et al. 2017). It has also been shown that caffeine produces analgesic effects and thus may improve

112   performance similarly by reducing pain perception allowing higher exercise intensities to be produced at the same

113   level of pain perception, or again deterring task disengagement due to reaching maximum tolerable pain levels

114   (Motl et al. 2003; Motl et al. 2006; Astorino et al. 2011; Duncan et al. 2013). Indeed, relative muscular endurance

115   typically does not change with interventions including resistance training, but where it does it has been speculated

116   this may be due to reductions in perceived discomfort (Fisher et al., 2020). However, both the perceived effort and

117   perceived pain reducing effects of caffeine have only been shown with higher doses (4-10mg$\cdot$kg^{-1}).

118   With the above in mind, the aim of this study was to consider the effects of a low caffeine dose (100mg /

119   <2mg$\cdot$kg^{-1}) compared to a placebo upon maximal strength and relative muscular endurance tasks, in addition to

120   perceptions of effort and discomfort, at both heavier- and lighter-loads (70% and 30% MVC, respectively) in a

121   female population. In this study design we have utilised isometric knee extension strength testing, and time to task

122   failure at %MVC. We hypothesised that caffeine would positively impact MVC, as well as TTF at 30% MVC and be

123   related to the perceptual effects of caffeine.

124

125   **Methods**

126   *Experimental Approach to the Problem*

127   The present study used a double-blind, randomised control and crossover counterbalanced research design

128   whereby all participants completed caffeine and placebo conditions for maximal strength testing (MVC) of the

129   knee extensors and both heavier- (70% MVC) and lighter- (30% MVC) load isometric knee extension time to task

130   failure (e.g. all participants performed 4 conditions).

131   *Participants*

132   Following approval from Solent University Health, Exercise and Sport Science ethics committee (ethical

133   application reference number: wallg2018), 19 physically active female participants (age range 18-35 years, mean (±

134   SD) age = 21.6 ±3.8 years, height = 1.68 ±0.07cm, mass = 67.9 ±8.4kg, body mass index = 24.2 ±2.8) were recruited

135   from a University campus. All participants were considered healthy based upon responses to a modified physical

136   activity readiness questionnaire (PARQ). Inclusion criteria required that all participants be habitual caffeine

137   drinkers (>100mg/day and recorded via a 4-day food diary based on Motl et al. 2006) and be free from

138   musculoskeletal injuries for which a knee extension task might be contraindicated, as well as not currently

139   undertaking a structured resistance training programme. All participants were provided a verbal briefing about the

140   study, provided a participant information sheet for their records, and completed an informed consent form.

141   Exclusion criteria included being pregnant, breast feeding ($\leq$ 6months), consuming androgenic anabolic steroids,

142   diabetic, hypertensive, consuming >300mg/day of caffeine.

143   *Familiarisation*

144   Prior to testing, each participant attended the laboratory where height and mass were recorded, and

145   paperwork were completed. The isokinetic dynamometer (Humac Norm, CSMi, Stoughton, MA) was set up to

146   ensure participant comfort, whilst the lateral epicondyle of the right knee was aligned with the axis of rotation on

147   the device. The cushioning pad of the leg extension was positioned central to the shin and seat and position

148   measurements were recorded for replication for each condition for each participant. All participants confirmed

149   right leg dominance when asked with which leg they would kick a football with and thus, the right leg was used for

150   testing for all conditions. Following set-up each participant completed MVC testing at 45° of knee extension and

151   the lighter load (30% MVC) condition as outlined below (data was not recorded) to provide familiarisation to

152   isokinetic testing and isometric time to task failure. During the familiarisation session participants were also

153   informed of the use of rating of perceived exertion-effort and rating of perceived exertion and perceived

154   discomfort scales (Steele et al. 2017). The scales and instructions are available on the Open Science Framework

155   (https://osf.io/ufvy8/).

156   *Blinding, Randomisation and Dosage*

157   A person external to the project was asked to label both the caffeine and placebo tablet as supplement 'A'

158   or 'B' and deposit each into an opaque container to ensure double blinding from both the researchers providing

159   the supplement and the participants. The caffeine consisted of 2 x Pro-Plus Tablets (a total of 100 mg caffeine),

160   and the placebo was 2 x Deva Vegan D2 Vitamin D 1200IU tablet (0.06mg D2). Vitamin D2 was selected based on

161   similarity and size to the caffeine tablet and since studies have shown this to be ineffective upon muscular strength

162   (Chiang et al. 2017). For the caffeine conditions the dosage of caffeine was maintained at 100mg per person since

163   this represents ecological validity for consumption (e.g. we believe a person is likely to consume the dosage

164   suggested on the packet not calculate a specific dosage based on their body mass). The dosage provided resulted

165   in a body mass relative dose at 1.50 ±0.18 mg·kg^{-1} (range = 1.1 to 1.85mg·kg^{-1}).[1]

166   *Testing*

167   On the morning of testing, participants had been instructed not to consume caffeine-containing food or

168   beverages. A sheet including drinks, food and medication to avoid was provided in advance to participants (in brief

169   this included; coffee, tea, chocolate, carbonated beverages, energy drinks of any kind, caffeine/energy gels,

170   chewing gum, supplement bars including protein and energy bars, weight-loss tablets, pain-relieving tablets

171   including codeine, paracetamol, ibuprofen, etc., and alcohol). Participants confirmed they had not participated in

172   strenuous exercise for 48 –hours prior to testing for each condition. Participants were not requested to attend the

173   testing sessions in a fasted state but were asked to replicate any foods consumed prior to the first testing

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[1] For context and comparison, an 8.4fl·oz/250ml can of Red Bull contains 80mg of caffeine, equal to 1.17 mg·kg^{-1} for
the present participants.

174   condition for the latter conditions. Participants attended the laboratory for testing between 8am and 11am, and

175   testing time was standardized for each participant across all conditions.

176   Participants returned no less than 6 days following the familiarisation for the first testing session to

177   eliminate the effects of any delayed onset muscle soreness. Each participant received either supplement 'A' or 'B'

178   (selected at random via a random letter generator) and was asked to consume it together with 150ml of tap water

179   (Smit and Rogers 2000). After 60 minutes , during which no food consumption or physical activity was permitted,

180   and toilet breaks and water consumption were logged, the participant was asked to complete a brief 5-minute

181   warm-up on a cycle ergometer (Monark, Ergomedic 874e) up to 60% age-predicted maximum heart rate to warm

182   key muscles (Fisher and Steele 2017). Following this, the participant completed a maximal voluntary contraction

183   (MVC) at 45° knee extension. Participants were instructed to gradually build up to a maximal effort over 3 seconds

184   and were instructed to gradually reduce their effort once it was clear that a max torque had been achieved (i.e.

185   when the torque reading was no longer increasing). After 30 seconds rest, the participant completed the isometric

186   leg extension task to failure. The lever arm was maintained at 45° knee extension and the participant was

187   provided visual feedback on a display screen of what force to maintain (70% or 30% for heavier- and lighter-load

188   conditions, respectively) with an upper and lower bar of ±5% (e.g. if MVC was 100Nm then for the 70% condition a

189   bar was shown at 70Nm with an upper and lower bar 3.5Nm above and below, respectively). Verbal

190   encouragement was provided throughout to ensure maximal exerted effort (Timmins and Saunders 2014), and if

191   they fell below the bottom torque limit then they were encouraged to attempt to regain their set torque output.

192   The task was ceased when the participant could not maintain the required force despite attempting to with

193   maximal effort. Rating of perceived effort (RPE) and rating of perceived discomfort (RPD) was measured and

194   recorded immediately following the isometric knee extension task (Steele et al. 2017) along with time to task

195   failure (TTF; seconds).

196   For the successive 3 testing sessions with no less than 6 days recovery between, participants repeated the

197   testing process as described above. Each participant was randomly assigned a supplement and condition from

198   their remaining allocation, e.g. each participant had 2 x 'A' and 2 x 'B' supplements, for both heavier- and lighter-

199   load conditions (70% and 30% MVC, respectively).

200   *Statistical analysis*

201   The independent variables were the training load (70% MVC and 30% MVC) and the supplement condition

202   (placebo and caffeine). The dependent variables included MVC, TTF, RPE, and RPD. All analysis was done using the

203   "lme4" package (Bates et al. 2015) and "lmerTest" in R (v3.6.1; R Foundation for Statistical Computing, Vienna,

204   Austria. URL http://www.R-project.org/). Linear mixed modelling was used to analyse all outcomes using

205   Restricted Maximum Likelihood estimation with participants as a level 3 variable, 'Load' (70% MVC and 30% MVC)

206   as a level 2 variable, and 'Condition' (placebo and caffeine) as a level 1 variable. 'Load' and 'Condition' were

207   modelled as fixed factors with random intercepts by participants included. For MVC only Condition as examined as

208   a factor with 4 separate observations per participant and 2 per condition due to this outcome being measured at

209   the beginning of every trial. Estimated marginal means with 95% confidence intervals were produced using the

210   "emmeans" package from each model (for each Condition for MVC, and for each Condition by Load for all other

211   dependent variables) in addition to pairwise contrasts. Contrasts were also performed with an equivalence testing

212   approach and 90% confidence intervals. Equivalence bands were determined from reliability data for MVC taken

213   from our laboratory using the same set-up as in the present study. The half-width of the minimal detectable

214   change % (6.98%) was used. Because we did not have similar reliability data for TTF we opted to use the same

215   relative minimal detectable change value for this dependent variable also in setting equivalence bands. The

216   absolute equivalence bands for MVC and TTF were ±6.45 Nm and ±14.25 seconds respectively. For RPE and RPD

217   we used the half-width of the minimal detectable change determined from previously published reliability data for

218   these scales (Steele, et al., 2017). The absolute equivalence bands for RPE and RPS were ±1.18 and ±1.40

219   respectively. All tests were conducted with $\alpha = 0.05$ for determination of statistical significance. In addition, data

220   visualisation included plotting individual raw data and estimated marginal means for repeated measures between

221   condition, in addition to pairwise contrasts with both 95% and 90% confidence intervals and equivalence bands.

222   Standardised effect sizes were calculated as Cohen's *d* (1992), and interpreted using Cohen's thresholds (>0.2 to

223   <0.5 'small'; >0.5 to <0.8 'moderate'; >0.8 'large') using the eff_size() function in the emmeans package.

224

225   **Results**

226   *MVC*

227   A statistically significant main effect of Condition was found in the linear mixed model for MVC ($F_{(1,56)}$ =

228   7.906, p = 0.007) with a higher MVC for caffeine (caffeine = 92.8 Nm [78.5 to 107.0 Nm], placebo = 82.6 Nm [68.4

229   to 96.8 Nm]). Cohen's *d* for the between condition contrast was 0.65 [0.15 to 1.14]. Equivalence testing did not

230   reveal a statistically significant effect ($t_{(56)}$ = -1.141, p = 0.129) for the pairwise contrast. Visual inspection of figure 1

231   reveals that traditional hypothesis testing excludes a null hypothesis of 0 Nm difference between caffeine and

232   placebo with a greater MVC seen for caffeine. However, the 95% confidence intervals do not exclude the upper

233   limit of the equivalence bands and so it is unclear whether there is a meaningful effect of caffeine upon MVC.

234   *INSERT FIGURE 1 AROUND HERE*

235   *TTF*

236   There was no statistically significant main effect of Condition found in the linear mixed model for TTF

237   ($F_{(1,54)}$ = 1.431, p = 0.2368) though there was a significant main effect of Load ($F_{(1,54)}$ = 1.431, p < 0.001) with greater

238   TTF for 30% MVC (caffeine[30% MVC] = 204.1 seconds [172.1 to 236.1 seconds], placebo[30% MVC] = 178.2

239   seconds [146.2 to 210.2 seconds], caffeine[70% MVC] = 65.3 seconds [33.3 to 97.3 seconds], placebo[70% MVC] =

240   62.1 seconds [30.0 to 94.1 seconds]). There was also no statistically significant interaction effect of Condition x

241   Load ($F_{(1,54)}$ = 0.870, p = 0.355). Cohen's *d* for the between condition contrast was 0.49 [-0.17 to 1.15] in 30% MVC,

242   and 0.06 [-0.59 to 0.71] in 70% MVC. Equivalence testing also did not reveal a statistically significant effect for

243   Condition either in 30% MVC ($t_{(54)}$ = 0.679, p = 0.750) or 70% MVC ($t_{(54)}$ = -0.640, p = 0.262) for the pairwise

244   contrasts. Visual inspection of figure 2 reveals that traditional hypothesis testing fails to exclude a null hypothesis

245   of 0 Nm difference between caffeine and placebo, yet the interval estimates are insufficiently precise to infer

246   equivalence between the conditions

247   *INSERT FIGURE 2 AROUND HERE*

248   *RPE*

249   There was no statistically significant main effect of Condition found in the linear mixed model for RPE

250   ($F_{(1,54)}$ = 0.518, p = 0.475) or of Load ($F_{(1,54)}$ = 3.056, p = 0.086), and no statistically significant interaction effort of

251   Condition x Load ($F_{(1,54)}$ = 0.095, p = 0.759) with RPE appearing similar across all trials (caffeine[30% MVC] = 8.26

252   [7.65 to 8.87], placebo [30% MVC] = 8.00 [7.39 to 8.61], caffeine[70% MVC] = 8.63 [8.02 to 8.24], placebo[70%

253   MVC] = 8.53 [7.92 to 9.14]). Cohen's d for the between condition contrast was 0.24 [-0.42 to 0.89] in 30% MVC,

254   and 0.09 [-0.56 to 0.74] in 70% MVC. Equivalence testing revealed a statistically significant effect for Condition in

255   both 30% MVC ($t_{(54)}$ = -2.528, p = 0.007) and 70% MVC ($t_{(54)}$ = -2.964, p = 0.002) for the pairwise contrasts. Visual

256   inspection of figure 3 reveals that across both 30% MVC and 70% MVC there was equivalence in RPE between

257   caffeine and placebo.

258   *INSERT FIGURE 3 AROUND HERE*

259   *RPD*

260   There was no statistically significant main effect of Condition found in the linear mixed model for RPE

261   ($F_{(1,54)}$ = 1.772, p = 0.189) or of Load ($F_{(1,54)}$ = 0.088, p = 0.769), and no statistically significant interaction effort of

262   Condition x Load ($F_{(1,54)}$ = 1.072, p = 0.305) with RPD appearing similar across all trials (caffeine[30% MVC] = 8.00

263   [7.26 to 8.74], placebo[30% MVC] = 7.16 [6.42 to 7.89], caffeine[70% MVC] = 7.53 [6.79 to 8.26], placebo[70%

264   MVC] = 7.42 [6.69 to 8.16]). Cohen's d for the between condition contrast was 0.54 [-0.11 to 1.20] in 30% MVC,

265   and 0.07 [-0.58 to 0.72] in 70% MVC. Equivalence testing revealed a statistically significant effect for Condition in

266   the 70% MVC ($t_{(54)}$ = -2.572, p = 0.006) but not 30% MVC ($t_{(54)}$ = -1.108, p = 0.136) for the pairwise contrasts. Visual

267   inspection of figure 4 reveals that for 70% MVC there was equivalence in RPD between caffeine and placebo.

268   *INSERT FIGURE 4 AROUND HERE*

269   **Discussion**

270   The present study considered the effects of low doses of caffeine upon maximal force (MVC) and time to

271   task failure (TTF) at 30% and 70% MVC in females. The aim of the study was to better understand whether low

272   caffeine doses can impact maximal strength (MVC) performance as well as affect relative muscular endurance

273   (TTF) and whether this was associated with an effect of reducing perceptions of effort or discomfort. To our

274   knowledge this is the first study to consider the impact of low doses of caffeine ($<2mg \cdot kg^{-1}$) upon MVC and TTF for

275   heavier- and lighter-loads in females. We believe our study represents an ecologically valid approach since people

276   typically consume a predetermined absolute dosage of caffeine (e.g. 2 x Pro-Plus tablets; equating to a total of

277   100mg caffeine) and rarely calculate a specific dosage based on their body mass. Our main findings were that

278   100mg caffeine ($\sim 1.5mg \cdot kg^{-1}$) supported an increase in strength, but not relative muscular endurance compared to

279   a placebo condition. These results are discussed in greater detail below.

280

281   MVC

282   Our analyses revealed a significant effect for caffeine upon MVC in line with previous research showing

283   positive effects upon strength as a result of caffeine ingestion (Grgic, Sabol et al. 2019c). Thus, even at low doses

284   caffeine may have the potential to positively impact maximal force production. However, whilst analyses did reveal

285   a statistically significant effect (i.e. excluding a zero effect), the confidence intervals did not exclude the upper

286   equivalence bands (Figure 1B) and therefore it is unclear how meaningful this increase in MVC is. However, the

287   standardised effect size (Cohen's d) for the caffeine compared to placebo condition for MVC was moderate ($d =$

288   0.645 [0.155 to 1.14]) which interestingly is larger than that reported in meta-analyses considered in a recent

289   umbrella review (Grgic et al., 2019a). Though, the inclusion of the upper equivalence band and the point and

290   interval estimates of prior meta-analyses in the confidence interval range for our estimate suggests that the true

291   population effect may be lower and questions its meaningfulness. Further, prior research examining maximal

292   strength in females has shown generally trivial to small effects at best (Goldstein et al., 2010; Sabblah et al., 2015).

293   However, we should recognize that caffeine consumption in females might stimulate very individual responses to

294   MVC based on both genetic factors and the use of an oral contraceptive pill (Guest et al. 2018; Abernethy and

295   Todd 1985). Inspection of the individual participant data in Figure 1 suggests there was considerable inter-

296   individual variation. However, the extent to which this is *true* inter-individual variation in response to caffeine as

297   opposed to merely test-retest variation is unclear and future research should consider employing replicated

298   randomised cross-over designs to investigate this (Atkinson et al. 2019).

299   TTF

300   As expected, and supported by previous research, there was a statistically significantly longer time to task

301   failure for the 30% MVC conditions compared to the 70% MVC conditions (30% MVC: caffeine = 204.1 seconds,

302   placebo = 178.2 seconds; 70% MVC: caffeine = 65.3 seconds, placebo = 62.1 seconds). The body of literature has

303   reported that when exercising with lighter loads a person can/must exercise for considerably longer to reach

304   momentary failure (Fisher and Steele 2017; Stuart et al. 2018). In contrast to previous research, our analyses

305   revealed no statistically significant difference for TTF as result of caffeine compared to placebo ingestion. Grgic et

306   al. (2019c) recently reported significant increases in relative muscular endurance at 60%1RM at all doses

307   examined, though this study was in males only. Sabblah et al. (2015) found that, though not significant, any effect

308   on relative muscular endurance at 40%1RM appeared to be larger in males compared with females. It is worth

309   considering however that with increases in strength resultant from interventions such as resistance training,

310   relative muscular endurance typically does not change (Fisher et al. 2020). In previous studies, strength is normally

311   measured using 1RM on a separate day to the placebo and caffeine conditions and so where there are changes this

312   may be due to increased strength from supplementation resulting in the load used for muscular endurance testing

313   being relatively less. In the present study we tested MVC on the day of each condition and after supplementation.

314   Thus, the lack of change in relative muscular endurance may be due to the fact that, though strength (MVC)

315   increased, the load used for muscular endurance testing was set relative to that MVC.

316   However, while there was no statistically significant effect for Condition, or Condition x Load interaction,

317   descriptively the lighter load (30% MVC) condition appears to differ between caffeine and placebo conditions

318   (204.1 ±97.32 seconds, and 160.95 ±81.31 seconds, respectively). While this was not statistically significant

319   (neither excluding the upper equivalence bands nor a zero effect), a mean time change from placebo to caffeine of

320   ~45 seconds might be practically meaningful. The standardised effect size for TTF following caffeine ingestion

321   compared to placebo for the lighter load condition was moderate (d = 0.489 [-0.169 to 1.146]). This effect size is

322   not too dissimilar from those reported in other meta-analyses though again the interval estimate suggests it may

323   be lower (Grgic et al., 2019a). Warren et al. (2010) suggested that endurance improvements are the result of

324   greater muscle fibre recruitment in the caffeine condition. However, the moderate effect for caffeine in the low

325 load condition (30% MVC) was not evident in the higher load condition (70% MVC). At heavier loads

326 electromyographic amplitude (a proxy for motor unit recruitment) is higher than at lighter loads (Fisher et al.

327 2017). As such, caffeine might be less likely to positively influence muscular endurance by motor unit recruitment

328 in a heavier load condition. In contrast, at lighter loads caffeine ingestion might positively influence motor unit

329 cycling and re-recruitment to sustain the force requirements, and thus enhance muscular endurance.

330   In addition, prior research has suggested that caffeine might impact on TTF due to its effects upon

331 perceived effort and/or perceived pain (Motl et al. 2003; Motl et al. 2006; Astorino et al. 2011; Duncan et al. 2013;

332 de Morree et al. 2014; Smirnaul et al. 2017). Previous studies comparing lighter- and heavier-load exercise to

333 momentary failure have reported similar values for effort, but higher values for discomfort for a lighter load

334 condition (Fisher and Steele 2017; Stuart et al. 2018). Indeed, improvements in measures of relative muscular

335 endurance have been speculated to be in part due to greater tolerance of perceived discomfort (Fisher et al. 2020).

336 Thus, any performance enhancement in lighter- compared to heavier-load exercise may be due to effects upon

337 perceptual variables. As such we measured both perceived effort (RPE) and perceived discomfort (RPD).

338 RPE and RPD/Perceptual responses

339   RPE and RPD were recorded immediately after completing the knee extension task. There were no

340 significant differences between caffeine and placebo conditions for RPE which, whilst not maximal in value (e.g.

341 10) for all participants, supports that the effort level was likely similar across all conditions. Indeed, equivalence

342 testing was statistically significant suggesting that the RPEs reported were equivalent across conditions and loads.

343 This is somewhat contradictory of previous research which has reported lower RPE values following caffeine

344 ingestion *during* exercise, though concordant with no differences in RPE *at* or *after* task failure (Doherty and Smith

345 2005). This might be expected given that task failure should theoretically represent a ceiling for RPE and result in

346 maximal or near maximal values irrespective of performance (even when affected by supplementation). Indeed,

347 our results supported that RPE was statistically equivalent at task failure between conditions. Doherty and Smith

348 (2005) however reported that the reduction in RPE *during* constant load exercise explained 29% of the variance in

349 performance. Though a limitation of our study was that we did not measure RPE during each condition (and thus

350 does not rule out RPE as potentially impacting TTF), a strength was the consideration of both ratings of perceived

351   effort and discomfort where previous studies have generally failed to differentiate between the two. Since caffeine

352   is shown to produce analgesic effects that may improve performance by reducing pain perception (Motl et al.

353   2003; Motl et al. 2006; Astorino et al. 2011; Duncan et al. 2013), our data might simply support that effort was

354   equivalent and unaffected by conditions independently of pain/discomfort perception.

355   Analyses of RPD also revealed no significant differences between heavier- or lighter-load conditions or

356   between placebo or caffeine conditions. This could be interpreted to suggest that caffeine had no analgesic effects

357   upon the perception of discomfort during prolonged exercise to momentary failure with a lighter- compared to

358   heavier- load. That there were no differences between heavier- and lighter-load conditions (irrespective of caffeine

359   or placebo conditions) suggests that an isometric task performed for time to failure might differ in the perceived

360   discomfort incurred in comparison to performing traditional repetitions (e.g. both concentric and eccentric muscle

361   actions). Certainly, previous research has supported differences in perceived discomfort between heavier- and

362   lighter-load exercise (Fisher and Steele 2017; Stuart et al. 2018). Fisher and Steele (2017) reported RPD values for

363   dynamic knee extension exercise of 8.7 and 6.5 for lighter-load (50%MVC) and heavier-load (80%MVC),

364   respectively. Stuart et al. (2018) reported values of 6.3 for heavier-load (80%MVC) and 8.0 and 8.3 for lighter load

365   (50%MVC) for males and females, respectively. However, perceived discomfort values from the present study

366   using an isometric task were more similar (CAFF=8.0 and PLA=7.2 for 30%MVC and CAFF=7.5 and PLA=7.4 for

367   70%MVC). Previous literature has reported significantly greater values for pain and exertion for an isometric task

368   using 50%MVC compared to a dynamic task using 75%MVC when performed to momentary failure (Frey Law et al.

369   2010). This suggests the relationship for discomfort might be different for isometric compared to dynamic muscle

370   actions. Nonetheless, despite not finding statistically significant differences for perceived discomfort, we also did

371   not find that RPD was statistically equivalent in the lighter-load condition whereas it was for the heavier-load

372   condition. The standardised effect size for comparison of RPD between caffeine and placebo in the lighter-load

373   condition (d = 0.543 [-0.110 to 1.196]) was not too dissimilar form the standardised effect size found for TTF (d =

374   0.489 [-0.169 to 1.146]). But, contrastingly to the anticipated analgesic effects of caffeine, this suggested that

375   during the lighter-load condition participants rated *higher* perceptions of discomfort as a result of caffeine

376   supplementation. These, results question whether there may be either an effort reducing, or an analgesic effect of

377   caffeine that results in improved endurance under conditions of higher discomfort (i.e. lighter-loads) but this

378   should be examined in further research.

379   Limitations

380   It would be remiss not to discuss the limitations of the present study. Primarily, we did not include a non-

381   placebo control condition and as such we cannot be certain that a placebo effect was not evident. In addition, we

382   did not assess the effectiveness of blinding upon participants who might have experienced typical sensation of

383   increased arousal following caffeine consumption compared to placebo. Indeed, Saunders et al. (2016) suggest

384   that supplement identification can influence exercise performance. Furthermore, we did not measure blood

385   caffeine concentrations and thus the provision of a specific dose (100mg) combined with the potentially different

386   absorption rates as a result of oral contraceptive or genetic factors cannot be discounted. A further limitation is

387   the sample size in our study; however, we have presented a larger participant number than many previous studies,

388   and we believe the study design along with the sample size fairly represents the results obtained. Based on the

389   contemporary thinking surrounding a gene-caffeine interaction (Guest et al. 2018), as well as the possibility that an

390   oral contraceptive pill might impact the effects of caffeine upon the body (Abernethy and Todd 1985), future

391   research might consider genetic testing as well as consideration of the menstrual cycle and contraceptive use;

392   something which we failed to do. As such a larger sample size might become redundant in females where

393   assessment of the effects of caffeine could be measured based on individual variables. Also, we accept that larger

394   caffeine doses ($3\text{-}6\text{mg}\cdot\text{kg}^{-1}$ or larger) might produce more notable positive effects upon strength (Pickering and

395   Kiely 2019). However, our aim was not to identify optimal dose or current best practice, but rather fill a gap within

396   the literature (Spriet 2014) by considering whether, and how, low caffeine dosage impacts strength and muscular

397   endurance at heavier- and lighter-loads. In addition, as noted we did not measure RPE or RPD *during* the exercise

398   bouts and thus the lack of effects at task failure may miss any effect on the exercise bout. Lastly, we did not

399   measure other possible mechanisms through which the effects of caffeine are thought to impact maximal strength

400   and muscular endurance. Thus, the effects upon MVC seen here may be due to unmeasured mechanisms such as

401   blocking the binding of adenosine to A_1 and A_{2a} G-protein coupled receptor sites and increased sarcoplasmic

402   reticulum calcium release impacting upon the central nervous system and motor unit recruitment respectively

403   (Grgic et al., 2019b).

404   **Conclusions**

405   In the present study of females, we found a statistically significant effect of low dose caffeine (100mg,

406   equating to ~1.50 mg·kg^{-1}) upon knee extension MVC, though the meaningfulness of this performance

407   enhancement is less clear. Further, we did not find statistically significant effects of low dose caffeine upon TTF, or

408   RPE and RPD. Indeed, RPE was statistically equivalent for isometric knee extension to momentary task failure in all

409   conditions examined, and RPD for the heavier-load condition. As discussed herein, the dosage used represents an

410   ecologically valid approach (e.g. a specific absolute dosage rather than a personalised relative dose per kg of body

411   mass), and further, is representative of typical caffeinated beverages. Since caffeine consumption can present with

412   some deleterious side effects and withdrawal symptoms, we suggest a low caffeine dose (similar to that found in

413   typical caffeinated beverages) might be suitable practical approach to attain enhancements in muscular strength,

414   though not relative muscular endurance.

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Figure 1

Peak Torque (A) and difference in peak torque (B) between caffeine and placebo conditions
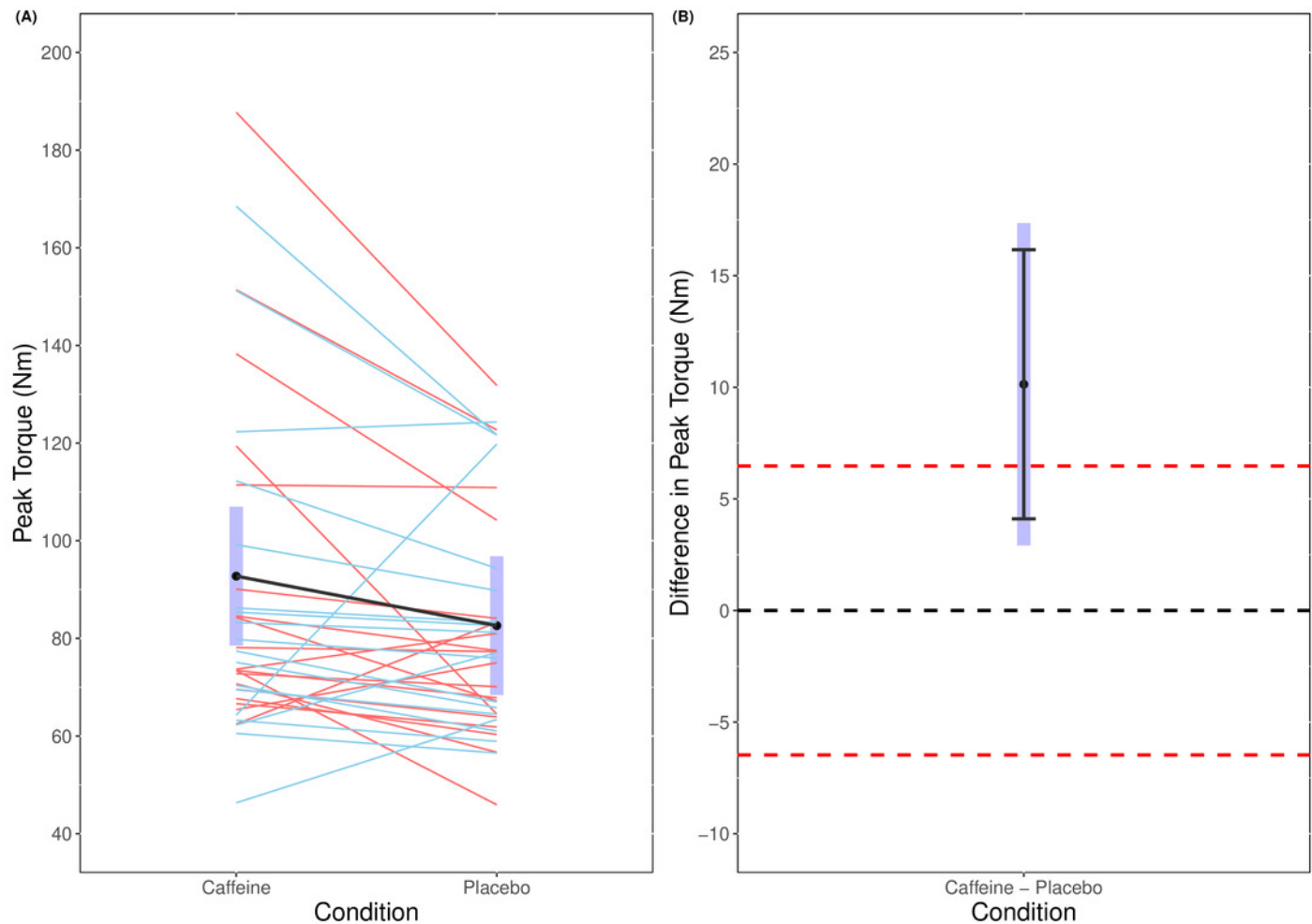
Figure 2

Time to task failure (A) and difference in time to task failure (B) for lighter (30% MVC) and heavier (70% MVC) load and between caffeine and placebo conditions
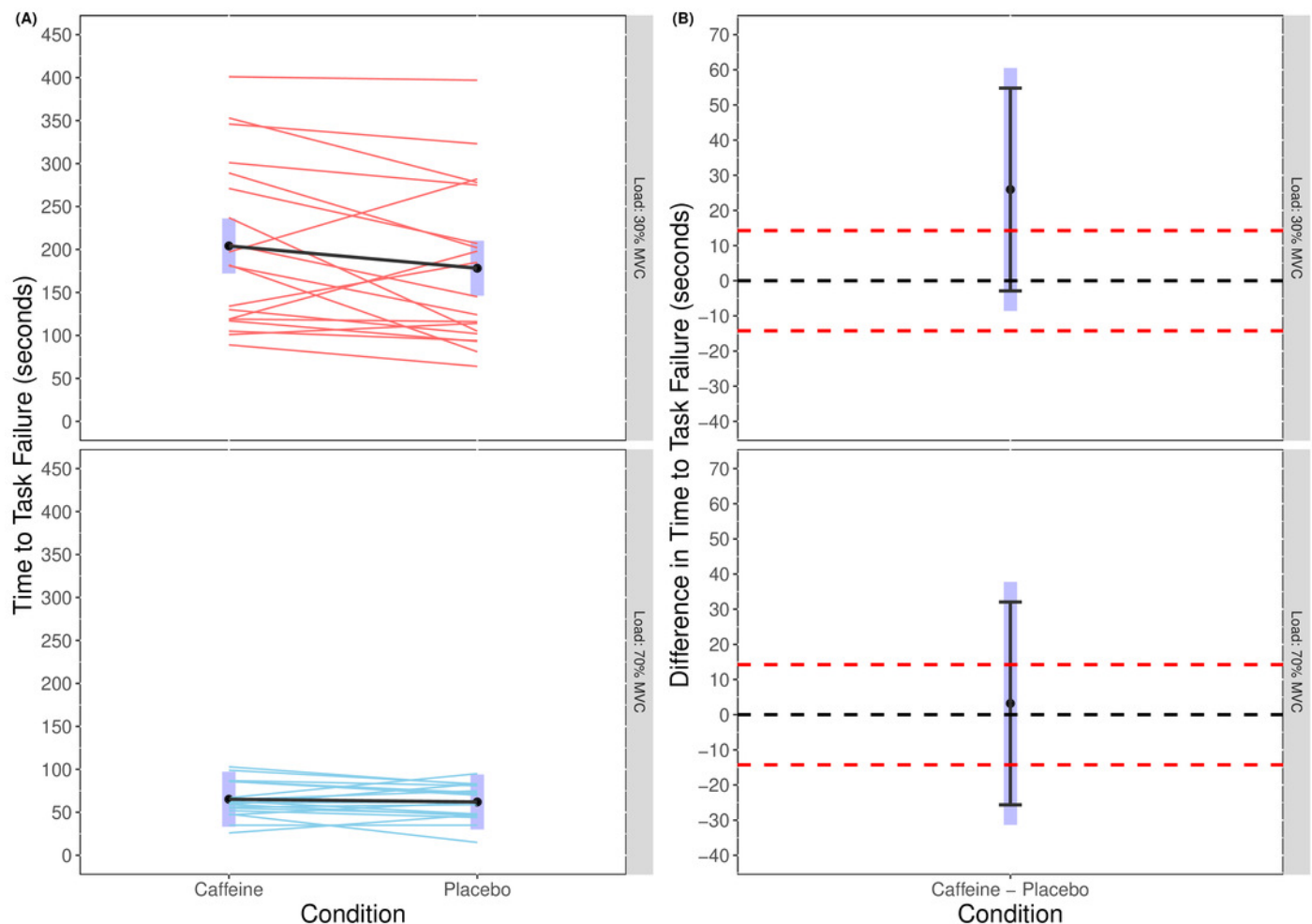
Figure 3

Rating of perceived effort (A) and difference in rating of perceived effort (B) for lighter (30% MVC) and heavier (70% MVC) load and between caffeine and placebo conditions
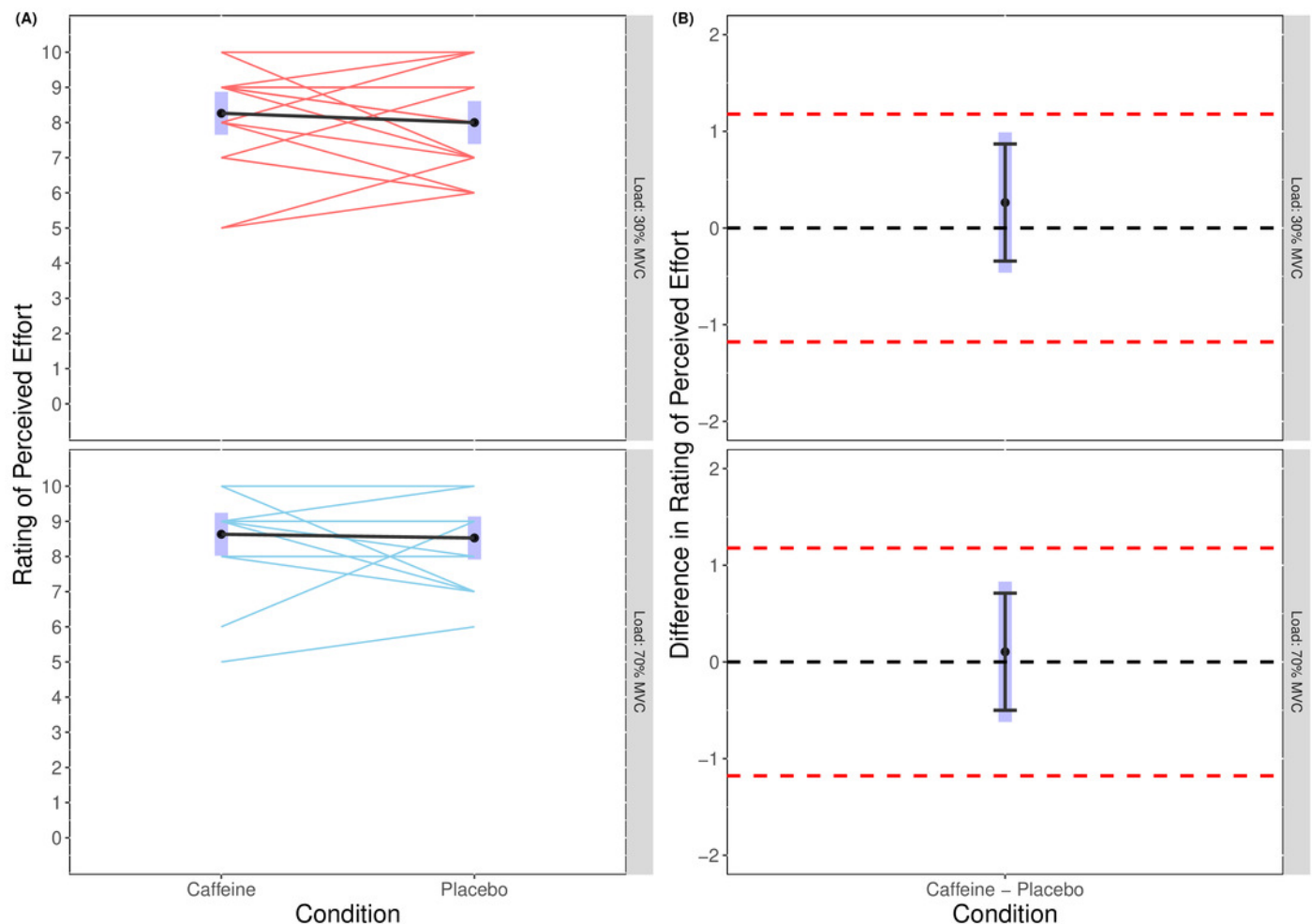
Figure 4

Rating of perceived discomfort(A) and difference in rating of perceived discomfort (B) for lighter (30% MVC) and heavier (70% MVC) load and between caffeine and placebo conditions