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1 **Normalisation of early isometric force production as a percentage of peak force, during**
2 **multi-joint isometric assessment**

3

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21

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27 Abstract

28 *Purpose:* To determine the reliability of early force production (50-, 100-, 150-, 200-, 250 ms)
29 relative to peak force (PF) during an isometric mid-thigh pull (IMTP) and assess the
30 relationships between these variables. *Methods:* Male collegiate athletes (n = 29; age: 21.1 ±
31 2.9 years; height: 1.71 ± 0.07 m; body mass: 71.3 ± 13.6 kg) performed IMTPs during two
32 separate testing sessions. Net PF and net force produced at each epoch were calculated. Within-
33 and between-session reliability were determined by using intraclass correlation coefficients
34 (ICC) and coefficient of variation (CV%). Additionally, Pearson's correlation coefficients and
35 coefficient of determination, were calculated to examine the relationships between PF and
36 time-specific force production. *Results:* Net PF and time-specific force demonstrated very high
37 to almost perfect reliability both within- and between-sessions (ICCs 0.82-0.97; CV% 0.35-
38 1.23%). Similarly, time-specific force expressed as a percentage of PF demonstrated very high
39 to almost perfect reliability both within- and between-sessions (ICCs 0.76-0.86; CV% 0.32-
40 2.51%). Strong to nearly perfect relationships ($r = 0.615-0.881$) exist between net PF and time-
41 specific net force, with relationships improving over longer epochs. *Conclusion:* Based on the
42 smallest detectable difference, a change in force at 50 ms expressed relative to PF >10% and
43 early force production (100-, 150-, 200- and 250 ms) expressed relative to PF of >2% should
44 be considered meaningful. Expressing early force production as a percentage of PF is reliable
45 and may provide greater insight into the adaptations to the previous training phase than PF
46 alone.

47

48

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50 **Key Words:** Isometric mid-thigh pull; rapid force production; strength; monitoring

51 **Introduction**

52 Maximal strength has been reported to be important for, and strongly associated with,
53 performance in athletic tasks.^{1,2} Moreover, increases in strength have been shown to result in
54 increases in athletic performance.^{2,3} Researchers have also reported strong associations
55 between dynamic strength and maximal isometric force production.^{4,5} In addition to
56 demonstrating the importance of a high maximal force capacity (i.e. a high maximal force
57 production), the ability to rapidly produce high levels of force is paramount during athletic
58 tasks, since there is a limited duration for the application of force during such activities.^{2,3} For
59 example, during high velocity sprinting, foot contact times can be much less than 250 ms, with
60 a progressive decline in contact time as running velocity increases.^{6,7}

61 Interestingly, there is a strong association between isometric peak force (PF) and isometric rate
62 of force development (RFD) during single joint knee extension^{8,9} and during the isometric
63 mid-thigh pull (IMTP).^{10,11} Additionally, these associations are stronger when RFD is
64 calculated over longer epochs (for example $r = 0.57$ at 30 ms [from onset of force production]
65 compared to $r = 0.89$ at 200 ms).⁹ Similarly, and as would be expected, force at specific time-
66 points (e.g. 20-, 40-, 60-... 200 ms) are also closely related to PF during single joint knee
67 extension.^{9,12} In addition, force at 100-, 150-, 200-, 250 ms has been reported to be associated
68 with PF during a multi-joint isometric mid-thigh pull,¹ with correlations between force at
69 specific time points (50-, 90-, 250 ms) and jump performance improving with an increase in
70 duration (later time-points).¹¹ It is important to reliably measure such changes in force
71 production, to monitor the training status of athletes and inform future programming.

72 Aagaard et al.¹² expressed isometric RFD across different epochs as a percentage of PF, during
73 isometric knee extensions, to monitor adaptations to resistance training. Results revealed
74 increases in early RFD (the first sixth of the time to PF), with the authors postulating that this

75 may have been due to increases in motor neuron recruitment, motor unit firing frequency,
76 myosin heavy chain isoform composition and sarcoplasmic reticulum calcium kinetics.
77 Andersen et al.⁸ also demonstrated that early RFD (epochs from 0-10 ms up to 0-100 ms),
78 expressed as a percentage of isometric PF indicates differential adaptations, in response to
79 heavy resistance training, compared to later stage RFD (>200 ms). Similar observations for
80 RFD expressed as a percentage of PF were also reported, with greater increases over longer
81 epochs, although both early and late RFD were associated with isometric PF. The authors
82 explained that a decrease in type IIX fibres may have negatively affected early RFD. Similar
83 differential adaptations in early and late RFD were reported by Oliveira et al.,¹³ with changes
84 in RFD explained by the increases in isometric PF. Additionally, Blazevich et al.¹⁴
85 demonstrated that changes in early force production and early RFD are influenced by increases
86 in fascicle length in response to training, which may partly explain these differential
87 adaptations in early and late force development.

88 When comparing RFD normalised to isometric PF between athletes and controls, athletes
89 demonstrated greater normalised RFD 0-50 ms, but not at other epochs.¹⁵ The authors attributed
90 this to differences in neural activation and contractile properties of the muscle and tendon. As
91 would be expected, absolute PF and RFD at all epochs were greater in athletes than controls.¹⁵
92 Similarly, Tillin et al.¹⁶ reported increases in force at specific time points (50-, 100-, 150 ms),
93 in response to four weeks of 'explosive' strength training, although, when normalised to
94 isometric PF, the only increase in force production occurred at 50 ms, possibly due to enhanced
95 agonist neural drive.

96

97 Isometric force at specific time-points has also been expressed in relation to PF, in an attempt
98 to explain training adaptations^{15,16} and differences between sexes,¹⁷ demonstrating that

99 differences in early force production between sexes may be explained by differences in
100 absolute force. While normalization of isometric force at specific time-points to PF during
101 MVIC has been performed in single joint assessments, to the authors' knowledge, this approach
102 has not been used in research using multi-joint isometric assessments of force. This is
103 somewhat surprising as performance during single joint assessments of force do not appear to
104 correlate well to athletic tasks.^{18,19} Multi-joint assessments, such as the IMTP demonstrate
105 strong correlations with performance in a range of athletic tasks.²⁰ Presenting data in this way
106 may provide the coach with information explaining whether changes in early force production
107 are in proportion to changes in PF, therefore identifying if the athlete should emphasize
108 maximal force production, or the ability to express force rapidly using appropriate training
109 methods. The aim of this investigation was, therefore, to determine the reliability of force at
110 specific time-points (50-, 100-, 150-, 200-, 250 ms) expressed relative to PF, assessed during
111 the IMTP. An additional aim was to identify if force at specific time-points are related to PF
112 during the IMTP, as has been observed during single-joint assessments.^{9,21} It was hypothesized
113 that force at specific time-points normalised to PF would be reliable and that PF and force at
114 specific time-points would be associated, in line with previous research.¹

115

116 **Methods**

117 ***Subjects***

118 Male collegiate athletes from a variety of sports (rowing, field hockey, soccer) volunteered to
119 participate in this investigation (n = 29, age 21.1 ± 2.9 years; height 1.71 ± 0.07 m; body mass
120 71.3 ± 13.6 kg; power clean one repetition maximum 1.12 ± 0.09 kg.kg⁻¹). All subjects provided
121 written informed consent, or parental assent as appropriate, and the study was approved by the
122 university's institutional review board, in accordance with the Declaration of Helsinki. Subjects
123 provided written informed consent and were all experienced in resistance training (resistance

124 training age 2.1 ± 0.6 years) and familiar with the testing protocols, from previous performance
125 of the IMTP used as a monitoring tool. Testing was completed at the start of the season, after
126 a 4-week block of strength training.

127

128 ***Design***

129 A repeated measures design was used, to determine the within- and between-session reliability
130 of force at specific time points (50-, 100-, 150-, 200-, 250 ms) normalised to PF during the
131 IMTP, and identify relationships between time-specific force production and PF. Subjects were
132 assessed twice (72 hours apart), to determine the reliability of the dependent variables. All
133 testing occurred in-season, immediately after a one-week break from resistance training, after
134 a previous four-week strength mesocycle. Testing was performed at the same time of day, with
135 subjects asked to maintain their normal dietary intake and avoid strenuous exercise for at least
136 48 hours prior to testing.

137 Prior to testing, subjects performed a non-fatiguing standardised warm up consisting of body
138 weight squats, forward and reverse lunges, and submaximal countermovement jumps. Further
139 familiarisation and warm up trials were performed prior to the maximal IMTP, as described
140 below.

141

142 ***Methodology***

143 ***Isometric Mid-thigh Pull***

144 Previously described procedures were adopted.^{20,22} An immovable cold rolled steel bar was
145 positioned at a height that replicated the start of the second pull phase of the clean on a custom
146 rack above a force platform. Once the bar height was established, the subjects stood on the
147 force platform with their hands strapped to the bar, using standard lifting straps.¹ Each subject

148 adopted the posture that they would use for the start of the second pull phase of the clean,
149 resulting in knee and hip angles of $139.5 \pm 3.3^\circ$ and $145.1 \pm 3.4^\circ$ respectively, in line with
150 previous research.^{20,22} Individual joint angles were measured using a goniometer, recorded and
151 standardised between testing sessions, in line with previous suggestions.²⁰

152 Each participant performed three warm-up trials, one at 50%, one at 75% and one at 90% of
153 their perceived maximum effort, separated by one minute of rest. Once body position was
154 stabilized (verified by watching the participant and the force-time record), the participants were
155 given a countdown of “3, 2, 1, Pull”. Any obvious pre-tension, determined as a force >50 N
156 above the subjects’ system mass (body mass + bar mass), was not permitted prior to initiation
157 of the pull. Subjects were instructed to pull against the bar “and push their feet into the ground
158 as fast and hard as possible”, which has previously been reported to produce optimal testing
159 results.²³ Each IMTP trial was performed for approximately five seconds, after at least one
160 second of quiet standing in position prior to the start of the pull,²⁰ and all participants were
161 given strong verbal encouragement during each trial. Participants performed three maximal
162 IMTP trials interspersed with two minutes of rest between trials. If PF during all trials did not
163 fall within 250 N of each other, the trial was discounted and repeated after a further two minutes
164 of rest, in line with previous recommendations.^{20,22}

165 Vertical ground reaction force data were collected using a portable force platform sampling at
166 1000 Hz (Kistler Instruments, Winterthur, Switzerland), interfaced with a laptop computer and
167 specialist software (Bioware 3.1, Kistler Instruments, Winterthur, Switzerland) that allows for
168 direct measurement of force-time characteristics. Raw unfiltered, force-time data was exported
169 for subsequent analysis in a bespoke Excel spreadsheet.

170

171

172

173 *Data Analysis*

174 The onset of force production was defined as an increase in force that was greater than five
175 standard deviations of force calculated during last 1 second immediately before the pull
176 commenced.²⁰ Body weight was subtracted from the original force-time curve to give the net
177 force-time curve to prevent inflation of the associations between PF and time-specific variables
178 which would occur if gross force was used. Net peak force was reported as the maximum force
179 across the recorded net force-time curve. Subsequently, net force at 50-, 100-, 150-, 200- and
180 250 ms was identified. For between-session and correlational comparisons, the mean of the
181 three trials was used.

182

183 *Statistical Analyses*

184 All statistical analyses were conducted in SPSS (version 26, IBM). Normality of all data was
185 determined via Shapiro-Wilk's test, with all variables normally distributed ($p > 0.05$).

186 Reliability was assessed using two-way mixed model intraclass correlation coefficients (ICC)
187 and 95% confidence intervals (95% CI), with the 3,1 model used to determine within session
188 reliability and the 3,k model used between sessions.²⁴ To determine the magnitude of the

189 ICC, the values were interpreted as poor (<0.50), moderate (0.50-0.74), high (0.75-0.90) and
190 excellent (>0.90).²⁴ Coefficient of variation percentages (CV%) were also calculated

191 (standard deviation / mean x 100) to determine the between session variability, with $<10\%$
192 considered acceptable.²⁵ The smallest detectable difference in change of the early force

193 production, expressed as a percentage of PF, was also calculated as follows: $(1.96 \times (\sqrt{2}) \times$
194 standard error of the mean [SEM]), with SEM calculated as: $(SD \text{ [pooled]} \times \sqrt{(1-ICC)})$. In

195 addition, Hedge's g effect sizes were calculated to determine if there were any meaningful
196 differences between testing sessions and classified as trivial (≤ 0.19), small (0.20 – 0.59),

197 moderate (0.60 – 1.19), large (1.20 – 1.99), and very large (2.0 – 4.0).²⁶

198 Pearson's correlation coefficients, with 95% CI, and coefficient of determination (R^2), were
199 calculated to determine associations between PF and force at 50-, 100-, 150-, 200- and 250 ms,
200 with the associated p values adjusted using Bonferroni post-hoc correction for multiple
201 comparisons, and correlations interpreted as <0.10 , $0.10-0.29$ $0.30-0.49$, $0.50-0.69$, $0.7-0.89$
202 and ≥ 0.90 as trivial, small, moderate, large, very large and nearly perfect, respectively.²⁶

203

204 **Results**

205 All force variables demonstrated good to excellent reliability both within- and between
206 sessions, with reliability tending to improve across longer time points. Coefficient of variation
207 values illustrated minimal variability ($<2.0\%$), while Hedge's g effect sizes highlighted only
208 trivial differences between sessions (Table 1).

209

210 Table 1: Within and between session reliability and variability of absolute isometric mid-thigh pull variables and time specific force variables
 211 expressed as a percentage of peak force

Variable	Session 1		Session 2		Between-Session Statistics			
	Mean (SD)	ICC (95%CI)	Mean (SD)	ICC (95%CI)	ICC (95%CI)	%CV	g	SDD
Force 50 ms (N)	1069 (237)	0.827 (0.705-0.910)	1042 (222)	0.849 (0.739-0.922)	0.914 (0.818-0.959)	1.23	0.12	21.6 (6.3%)
Force 100 ms (N)	1276 (346)	0.914 (0.845-0.957)	1269 (296)	0.861 (0.757-0.929)	0.925 (0.839-0.965)	0.35	0.02	4.0 (0.7%)
Force 150 ms (N)	1537 (453)	0.938 (0.880-0.967)	1537 (369)	0.849 (0.739-0.992)	0.926 (0.841-0.965)	0.40	0.00	3.8 (0.4%)
Force 200 ms (N)	1765 (494)	0.933 (0.878-0.967)	1745 (407)	0.849 (0.737-0.922)	0.929 (0.849-0.967)	0.44	0.04	9.9 (0.95%)
Force 250 ms (N)	1865 (502)	0.942 (0.896-0.970)	1840 (447)	0.894 (0.816-0.945)	0.954 (0.903-0.978)	0.70	0.05	11.7 (1.02%)
Peak Force (N)	2367 (680)	0.978 (0.960-0.989)	2390 (674)	0.965 (0.934-0.983)	0.977 (0.951-0.989)	0.72	0.03	6.9 (0.4%)
Force 50 ms (%)	46.3 (7.4)	0.764 (0.608-0.875)	44.7 (6.8)	0.724 (0.551-0.851)	0.821 (0.622-0.916)	2.51	0.22	0.020 (9.6%)
Force 100 ms (%)	57.9 (8.9)	0.786 (0.642-0.887)	54.4 (8.9)	0.724 (0.551-0.851)	0.831 (0.639-0.921)	0.68	0.39	0.005 (1.5%)
Force 150 ms (%)	66.0 (10.9)	0.797 (0.658-0.893)	65.7 (10.8)	0.722 (0.546-0.850)	0.866 (0.713-0.937)	0.32	0.03	0.003 (0.5%)
Force 200 ms (%)	75.7 (8.7)	0.834 (0.714-0.914)	74.4 (9.8)	0.858 (0.732-0.931)	0.815 (0.607-0.913)	1.19	0.14	0.011 (1.7%)
Force 250 ms (%)	79.6 (8.2)	0.786 (0.648-0.884)	77.9 (7.7)	0.813 (0.654-0.906)	0.801 (0.581-0.906)	1.53	0.21	0.013 (1.9%)

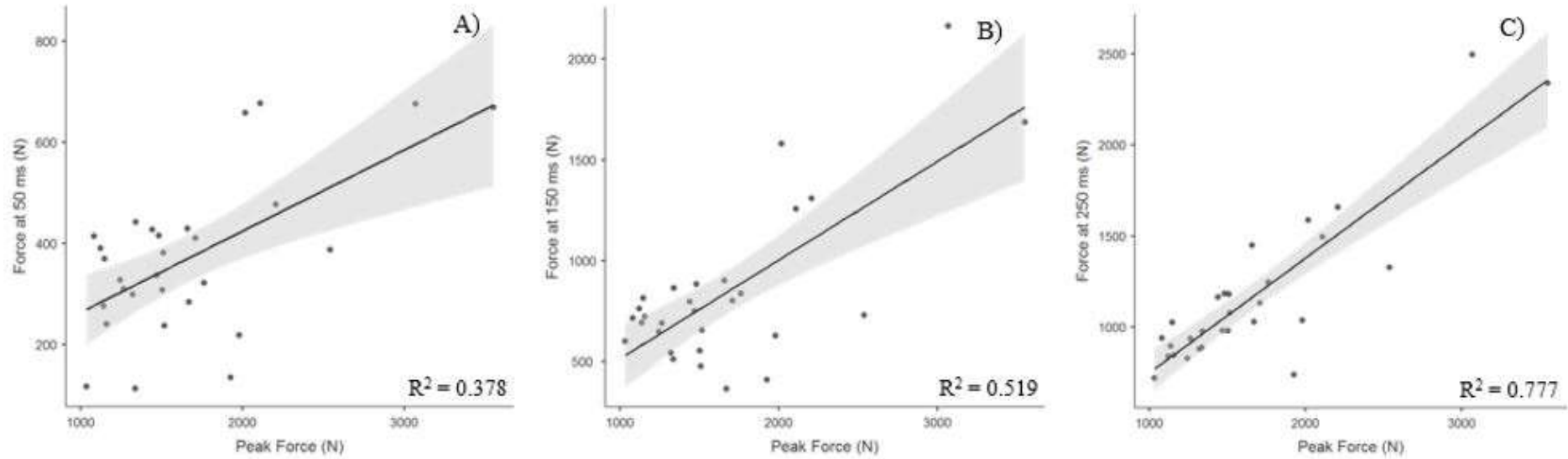
SD = Standard Deviation; ICC = Intraclass Correlation Coefficient; CI = Confidence Intervals; CV = Coefficient of Variation; g = Hedge's g Effect Size; SDD = Smallest Detectable Difference

213 Similarly, time-specific force variables expressed as a percentage of PF demonstrated high to
214 almost perfect reliability both within and between sessions. Coefficient of variation values
215 illustrated minimal variability (<3.0%), while Hedge's *g* effect sizes highlighted only trivial to
216 moderate differences between sessions (Table 1).

217 There were strong, significant correlations between force at each time-point and PF, with
218 progressive increases in the magnitude of the association from very strong to almost perfect,
219 as duration increased (50 ms, $r = 0.615$ [95% CI = 0.321-0.801], $R^2 = 0.378$; 100 ms, $r = 0.675$
220 [95% CI = 0.410-0.835], $R^2 = 0.456$; 150 ms, $r = 0.720$ [95% CI = 0.480-0.860], $R^2 = 0.518$;
221 200 ms, $r = 0.796$ [95% CI = 0.606-0.900], $R^2 = 0.634$; 250 ms, $r = 0.881$ [95% CI = 0.760-
222 0.943], $R^2 = 0.776$; $p < 0.001$) (Figure 1).

223

224



225

226 Figure 1: Associations between net force at A) 50 ms, B) 150 ms, C) 250 ms and net peak force. The shaded area represents the 95% confidence
227 intervals

228 Discussion

229 The aim of this investigation was to determine the reliability of net force at specific time-points
230 (50-, 100-, 150-, 200-, 250 ms) expressed relative to net PF, assessed during the IMTP, with
231 the results highlighting good to excellent reliability within- and between sessions, with low
232 variability and minimal differences between session, in line with the hypotheses. In addition,
233 net force at each time-point was strongly associated with net PF, demonstrating coefficients of
234 determination percentages of 38-78%, which progressively increased with an increase in the
235 duration over which net force was assessed.

236 The normalised time-specific net force values demonstrate lower reliability than the time-
237 specific force values and net PF, as the process of normalizing these values combines the
238 variability of both the time-specific net force and net PF. The normalised values, however, still
239 exhibited high reliability both within- and between sessions, with low variability and minimal
240 differences between sessions. Importantly, the smallest detectable difference of each of the
241 normalised time-specific force values were <10% and <2% for normalised force from 100-,
242 250 ms.

243 When monitoring training adaptations, it would be useful to determine if any changes in early
244 force production are in proportion to the change in net PF. For example, if an athlete's net PF
245 increases and there is a disproportionately low change in early net force production (percentage
246 of net PF decreases at specific time points), this may indicate that there is a deficit in rapid
247 force production. In this scenario, the focus of the subsequent mesocycle should emphasize
248 activities that focus on rapid force production rather than maximal force production.^{27,28} As
249 such, this would ensure that the higher force generating capacity, developed during the previous
250 mesocycle, can be appropriately expressed to enhance performance in sporting activities that
251 require rapid force production, depending on the requirements of the athlete's sport. In contrast,

252 if changes in early net force production are disproportionately greater than the change in net
253 PF (percentage of net PF increases at specific time points), it may be advantageous to
254 emphasize maximal force production during the subsequent mesocycle.^{27,28} As such,
255 expressing early net force production as a percentage of net PF should provide practitioners
256 with additional insight regarding the development of their athlete and assist in the appropriate
257 periodization of their training program.

258 It is worth noting however, that if net PF is low, indicating a low strength level, prioritizing
259 maximal force production may be preferential, as strength development in weak individuals
260 has been shown to be highly beneficial in terms of rapid force and power production.^{2,3,29,30} It
261 is also worth noting, however, that during periods of high-volume training (e.g. hypertrophy)
262 the associated residual fatigue is likely to result in an impaired ability to rapidly produce force.
263 Additionally, rapid force production is more responsive to increases in training intensity
264 compared to increases in volume.³¹

265 It is interesting that net PF explains 38-78% of variance in the force at specific time-points, and
266 somewhat logical that a stronger association was observed as the time-point increased, with
267 similar correlations previously reported in weightlifters.¹ These findings highlight the
268 importance of PF and therefore strength development, if the aim is to enhance an athlete's
269 ability to express high forces rapidly. Such observations are in line with numerous studies using
270 single joint assessment of force,^{9,21} the IMTP,¹ and observations during dynamic tasks.^{2,3}

271 Currently, the ideal percentage of net PF at different time points, along with how they relate to
272 performance in athletic tasks, is yet to be identified. The authors, therefore, suggest that such
273 thresholds be investigated in the future, along with the identification of the effect of different
274 training intensities and volumes on the changes in early net force production relative to net PF,
275 during the IMTP. Aagaard et al.¹² previously postulated that increases in early force production

276 are likely as a result of increases in motor neuron recruitment, motor unit firing frequency,
277 myosin heavy chain isoform composition and sarcoplasmic reticulum calcium kinetics.
278 Comparisons of changes in early force production and PF, as highlighted in this study, may
279 permit identification of whether changes are as a result of more efficient force production, or
280 as a result of increased PF.

281

282 **Practical Applications**

283 Coaches should consider changes in the percentage of net PF that can be produced during early
284 time points (100-, 150-, 200- and 250 ms) of >2% as meaningful, whereas changes in net PF at
285 50 ms, expressed as a percentage of net PF should be considered meaningful when >10%.
286 Researchers and practitioners should determine the percentage net PF that can be produced
287 during early time points, in addition to the absolute values, as this may provide greater insight
288 into the adaptations to the previous phase of training and equip the practitioner with
289 information regarding the requirements of the subsequent phase of training. If the percentage
290 of net PF has increased for a given time point, additional emphasis on maximal force
291 production (i.e. strength) may be warranted, while a decrease in percentage would indicate that
292 additional emphasis should be placed on the development of rapid force production (See Haff
293 and Nimphius³² for more detail regarding the application of such training principles). It is,
294 however, important for coaches to also understand the effects that each training phase is likely
295 to have on both PF and temporal aspects of force production, although further research should
296 be conducted in this area.

297

298

299

300 **Conclusions**

301 Expressing early net force production (50-, 100-, 150-, 200- and 250 ms) as a percentage of net
302 PF, during the IMTP, is reliable and may provide additional insight into the temporal aspects
303 of force production.

304

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309

310

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386 **Table and Figure Legends:**

387 Table 1: Within and between session reliability and variability of absolute isometric mid-thigh
 388 pull variables and time specific force variables expressed as a percentage of peak force

389
 390 Figure 1: Associations between net force at A) 50 ms, B) 150 ms, C) 250 ms and net peak
 391 force. The shaded area represents the 95% confidence intervals
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