The prediction of swim start performance based on squat jump force-time characteristics

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Background: Depending on the stroke and distances of the events, swim starts have been estimated to account for 0.8 % to 26.1 % of the overall race time, with the latter representing the percentage in a 50 m sprint front crawl event (Cossor & Mason 2001) . However, it is still somewhat unclear what are the key physiological characteristics underpinning swim start performance. The primary aim of this study was to develop a multiple regression model to determine key lower body force-time predictors using the squat jump for swim start performance as assessed by time to 5 m and 15 m in national and international level swimmers. A secondary aim was to determine if any differences exist between males and females in jump performance predictors for swim start performance. Methods: A total of 38 males (age 21 ± 3.1 years, height 1.83 ± 0.08 m, body mass 76.7 ± 10.2 kg) and 34 females (age 20.1 ± 3.2 years, height 1.73 ± 0.06 m, body mass 64.8 ± 8.4 kg) who had competed at either an elite (n = 31) or national level (n = 41) participated in this study. All tests were performed on the same day, with participants performing three bodyweight squat jumps on a force platform, followed by three swim starts using their main swimming stroke. Swim start performance was quantified via time to 5 m and 15 m using an instrumented starting block. Results: Stepwise multiple linear regression with quadratic fitting identified concentric impulse and concentric impulse^2 as statistically significant predictors for time to 5 m (R^2 = 0.659) in males. With time to 15 m, concentric impulse, age and concentric impulse^2 were statistically significant predictors for males (R^2 = 0.807). A minimum concentric impulse of 200 – 230 N.s appears required for faster times to 5 m and 15 m, with any additional impulse production not being associated with a reduction in swim start times for most

male swimmers. Concentric impulse, Reactive strength index modified and concentric mean power were identified as statistically significant predictors for female swimmers to time to 5 m (R^2 = 0.689). Variables that were statistically significant predictors of time to 15 m in females were concentric impulse, body mass, concentric rate of power development and Reactive strength index modified (R^2 = 0.841). Discussion: The results of this study highlight the importance of lower body power and strength for swim start performance, although being able to produce greater than 200 or 230 N.s concentric impulse in squat jump did not necessarily increase swim start performance over 5 m and 15 m, respectively. Swimmers who can already generate greater these levels of concentric impulse may benefit more from improving their rate of force development and/or technical aspects of the swim start performance. The sex-related differences in key force-time predictors suggest that male and female swimmers may require individualised strength and conditioning programs and regular monitoring of performance.

1   **The prediction of swim start performance based on squat jump force-time characteristics**

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4 **Abstract**

5 Background: Depending on the stroke and distances of the events, swim starts have been
6 estimated to account for 0.8% to 26.1% of the overall race time, with the latter representing the
7 percentage in a 50 m sprint front crawl event (Cossor & Mason 2001). However, it is still
8 somewhat unclear what are the key physiological characteristics underpinning swim start
9 performance. The primary aim of this study was to develop a multiple regression model to
10 determine key lower body force-time predictors using the squat jump for swim start performance
11 as assessed by time to 5 m and 15 m in national and international level swimmers. A secondary
12 aim was to determine if any differences exist between males and females in jump performance
13 predictors for swim start performance.

14 Methods: A total of 38 males (age 21 ± 3.1 years, height 1.83 ± 0.08 m, body mass 76.7 ± 10.2
15 kg) and 34 females (age 20.1 ± 3.2 years, height 1.73 ± 0.06 m, body mass 64.8 ± 8.4 kg) who
16 had competed at either an elite (n = 31) or national level (n = 41) participated in this study. All
17 tests were performed on the same day, with participants performing three bodyweight squat
18 jumps on a force platform, followed by three swim starts using their main swimming stroke.
19 Swim start performance was quantified via the time to 5 m and 15 m using an instrumented
20 starting block.

21 Results: Stepwise multiple linear regression with quadratic fitting identified concentric impulse
22 and concentric impulse^2 as statistically significant predictors for time to 5 m ($R^2 = 0.659$) in
23 males. With time to 15 m, concentric impulse, age and concentric impulse^2 were statistically
24 significant predictors for males ($R^2 = 0.807$). A minimum concentric impulse of $200 - 230$ N.s
25 appears required for faster times to 5 m and 15 m, with any additional impulse production not
26 being associated with a reduction in swim start times for most male swimmers. Concentric
27 impulse, Reactive strength index modified and concentric mean power were identified as
28 statistically significant predictors for female swimmers to time to 5 m ($R^2 = 0.689$). Variables
29 that were statistically significant predictors of time to 15 m in females were concentric impulse,
30 body mass, concentric rate of power development and Reactive strength index modified ($R^2 =$
31 0.841).

32 Discussion: The results of this study highlight the importance of lower body power and strength
33 for swim start performance, although being able to produce greater than 200 or 230 N.s
34 concentric impulse in squat jump did not necessarily increase swim start performance over 5 m
35 and 15 m, respectively. Swimmers who can already generate greater these levels of concentric
36 impulse may benefit more from improving their rate of force development and/or technical
37 aspects of the swim start performance. The sex-related differences in key force-time predictors
38 suggest that male and female swimmers may require individualised strength and conditioning
39 programs and regular monitoring of performance.

40

41 **Introduction**

42 Swim start performance has been identified as a determining factor for success, especially in
43 sprint distance events, as it is the part of the race that the swimmer is travelling at the fastest
44 velocity (Cossor & Mason 2001; Tor et al. 2014). While the exact nature of starts may differ
45 between the four swimming strokes, there are three primary phases that contribute towards the
46 overall start performance. The block phase requires a quick reaction to the starting signal and a
47 large take-off velocity that is primarily horizontal in direction (Garcia-Hermoso et al. 2013). The
48 subsequent flight phase is an example of projectile motion, whereby the swimmer becomes
49 airborne and finishes when they contact the water (Slawson et al. 2013; Tor et al. 2014). The
50 flight phase is followed by the underwater phase, in which swimmers attempt to maintain a
51 streamlined position with their arms outstretched in front of the head to minimise velocity loss
52 while also performing multiple propulsive undulatory leg kicks (except in breaststroke) until
53 their head resurfaces before the 15 m mark (Formicola & Rainoldi 2015). The block, flight, and
54 underwater phase account for approximately 11%, 5%, and 84% respectively of the total start
55 time (Slawson et al. 2013). The average velocity during the underwater phase is highly
56 dependent on the take-off velocity acquired in the block phase, the horizontal distance obtained
57 in the flight phase, as well as the degree of streamlining and effectiveness of the undulatory leg
58 kicks during the underwater phase (Tor et al. 2014).

59 As close margins often exist between medallists in sprint swimming events, being able to
60 identify areas to achieve marginal gains in performance by tenths or even hundredths of a second
61 can make a difference in overall performance (Bishop et al. 2009). Previous research has
62 highlighted a key component of swim start performance is the ability to produce high forces off
63 the starting block. In a recent systematic review of eight cross-sectional studies, Thng et al.
64 (2019) observed significant correlations between vertical jump and lower body strength scores to
65 swim start performance in swimmers of a variety of standards, with these correlations typically
66 higher for the jump than strength tests. Specifically, near perfect correlations (r > 0.90) between
67 jump height or take-off velocity and swim start performance were observed in the eight studies.
68 These results highlight the importance of lower body power and strength as an important
69 component of swim start performance. However, out of the 8 cross-sectional studies identified in
70 the systematic review (Thng et al. 2019), only one study utilised the OSB11 start block
71 (OMEGA, Zurich, Switzerland) that is currently used in competitive swimming (Garcia-Ramos
72 et al. 2016a). The OSB11 start block which was introduced by FINA in 2010 has an angled kick
73 plate at the rear of the block that allows the swimmer to adopt a kick start technique. Honda et al.
74 (2010) have identified that the angled kick plate on the OSB11 start block is capable of
75 significantly improving both time to 5 m and 7.5 m, with a further 0.04 s improvement obtained
76 in the kick start compared to the track start technique performed on the previous starting block.
77 This is attributed to an increase in horizontal force application and subsequent take-off velocity
78 results from the additional contribution of the rear leg on the kick plate. This view of Honda et
79 al. (2010) was consistent with the findings of Slawson et al. (2013) who observed higher peak
80 horizontal and vertical force generation with the OSB11 start blocks in elite swimmers, with
81 these forces significantly correlated to a better start performance as assessed by block time, take-
82 off velocity and flight distance.

83   In addition, all of the studies described in the systematic review by Thng et al. (2019) only
84   involved correlational analyses. While correlations describe the nature of a relationship between
85   two variables, other statistical approaches such as multiple linear regression may provide more
86   information regarding what power and strength variables (hereafter referred to as force-time
87   characteristics) of jumping performance that best predict swim start performance in high
88   performance swimmers. The lack of research using the OSB11 start block and kick start
89   technique in these correlation studies needs to be addressed, as this relative lack of ecological
90   validity with the start technique used in seven of the eight published studies may limit the
91   generalisability to contemporary high-performance swimming.

92   Another limitation of the previous literature is the small sample sizes of recreational to sub-elite
93   swimmers (n = 7–27) and the relative focus on male swimmers at the expense of their female
94   counterparts. This is a concern as previous research has established differences in force and
95   power capabilities between males and females in other athletic activities (McMahon et al. 2017;
96   Rice et al. 2017). For example, a number of studies has observed that males are able to produce
97   higher velocities at the same percent of one repetition maximum and have a greater rate of force
98   development and countermovement jump height than females (Laffaye et al. 2014; McMahon et
99   al. 2017; Rice et al. 2017; Torrejon et al. 2019). Rice et al. (2017) concluded that this greater
100 jump height observed in males compared to females can be attributed to larger concentric
101 impulse and thus greater velocity throughout most of the concentric phase at take-off in the
102 countermovement jump. Further, the higher rate of force development and ability to produce
103 greater velocities at the same percentage of one repetition maximum in males may be a result of
104 greater muscle thickness and cross-sectional area, greater percentage of fast-twitch muscle fibres,
105 greater concentration of anabolic hormones and higher neural activity during muscle contractions
106 compared to females (Alegre et al. 2009). From a practical standpoint, these sex-related
107 differences in force-time characteristics suggests there might need to be some potential
108 differences in aspects of athletic monitoring and strength and conditioning programs between
109 high-performance male and female swimmers.

110 The primary objective of this study was to develop a multiple regression model to determine key
111 lower body force-time predictors for swim start performance using the squat jump in high
112 performance swimmers. Considering the potential sex differences in force-time characteristics
113 during jumping, a secondary aim was to determine if differences exists between males and
114 females in jump performance predictors for swim start performance.
115
116 **Materials & Methods**
117
118 **Study Design**
119 A cross-sectional study design was used to quantify the relationship between squat jump (SJ)
120 force-time variables to swim start performance as assessed by times to 5 m and 15 m in national
121 and international level swimmers. All tests were performed on the same day, with participants
122 first performing SJ testing on the force platform, followed by a swim start performance test with
123 a 30-minute recovery period in between each testing session.
124
125 **Participants**

126   Thirty-eight males and 34 females who had competed at either an elite (n = 31) or national level
127   (n = 41) in front crawl, butterfly or breaststroke participated in this study. Backstroke was
128   excluded due to the start being initiated from within the water, instead of on the elevated OSB11
129   starting block. Elite level swimmers comprised of swimmers who had competed internationally
130   in either the Olympics, Commonwealth Games or World Championships. National level
131   swimmers comprised of swimmers that have at least 2 years of experience in competing at a
132   national level and competed at the most recent national championships. Swimmers were required
133   to have at least 1 year of land-based resistance training experience under the supervision of a
134   strength and conditioning coach. All participants gave written informed consent to participate in
135   the study, which was conducted in accordance with the Declaration of Helsinki and approved by
136   Bond University Human Research Ethics Committee (0000016006), The University of
137   Queensland Human Research Ethics Committee (HMS17/41) and Swimming Australia Ltd.
138
139   **Methodology**
140
141   **Squat Jump test**
142   Prior to the SJ test, participants completed a dynamic lower body warm-up under the supervision
143   of a strength and conditioning coach. Following the warm-up, participants were given two
144   practice jumps before the test was conducted. Jumps were performed on a force platform
145   (ForceDecks FD4000, London, United Kingdom), with a sample rate of 1000 Hz. Participants
146   started in an upright standing position with their hands on their hips. They were then instructed
147   to adopt a squat position using a self-selected depth that was held for 3 seconds before they
148   attempted to jump as high as possible (Mitchell et al. 2017). A self-selected squat depth was
149   chosen as it has been reported to produce the greatest jump height and higher peak force outputs
150   in comparison to measured squat depths (Kirby et al. 2011). A successful trial was one that did
151   not display any small amplitude countermovement at the start of the jump phase on the force
152   trace (Sheppard & Doyle 2008). All participants were asked to perform three maximal intensity
153   SJ with a 30-second passive rest in between each effort.
154
155   The SJ trial with the highest jump height was kept for data analysis. Jump height was determined
156   by the conventional impulse-momentum method (Jump Height = $v^2/2g$, where v = velocity at
157   take-off and g = gravitational acceleration) (Heishman et al. 2019). Ground reaction force data
158   from the SJs were analysed using the commercially available ForceDecks software (ForceDecks,
159   London, United Kingdom). Out of the variables provided by ForceDecks, 46 variables, excluding
160   any left-to right asymmetry variables were initially extracted for use in further analysis.
161   Descriptions of the SJ variables are provided in the Electronic Supplementary Table S1.
162
163   **Swim start**
164   After completing a self-selected warm-up based on their usual pre-race warm-up routine,
165   participants then performed three maximal effort swim starts with their main swim stroke (front
166   crawl (n = 50), butterfly (n = 12), or breaststroke (n = 10) while wearing their regular swim
167   training swimsuits. Trials were started as per competition conditions and swimmers were
168   instructed to swim to a distance past the 15 m mark, in order to ensure that representative values
169   at the 15 m distance were obtained (Barlow et al. 2014). Two-minutes of passive recovery was
170   given between each trial (Tor et al. 2015b). The start with the fastest time to 5 m for each
171   individual with all swim strokes were selected for further analysis.

172

173 All 72 participants were included in the time to 5 m analysis irrespective of stroke performed, as
174 the technical execution of the swim start does not differ until after 5 m. To avoid the potential
175 confounding influence of the speed differences in both the underwater and swim phases of
176 butterfly and breaststroke, only front crawl was included for time to 15 m analysis as it
177 comprised of majority of the sample (n = 50).

178

179 Swim start performance were collected using a Kistler Performance Analysis System –
180 Swimming (KPAS-S, Kistler Winterthur, Switzerland), which utilises a force instrumented
181 starting block, constructed to match the dimensions of the Omega OSB11 block (KPAS-S Type
182 9691A1; Kistler Winterthur, Switzerland). Time to 5 m and 15 m were collected using five
183 calibrated high speed digital cameras collecting at 100 frames per second, synchronised to the
184 instrumented starting block using the KPAS-S. One camera was positioned 0.95 m above the
185 water and 2.5 m perpendicular to the direction of travel to capture the start and entry of swimmer
186 into the water, while the other three cameras were positioned 1.3 m underwater at 5 m, 10 m and
187 15 m perpendicular to the swimmer to capture the time to 15 m (Fig. 1) (Tor et al. 2015b). The
188 times to 5 m and 15 m were defined as the time elapsed from the starting signal until the apex of
189 the swimmers' head passed the respective distances (Tor et al. 2015b). An Infinity Start System
190 (Colorado Time Systems, Loveland, Colorado, USA) provided an audible starting signal to the
191 athletes as well as an electronic start trigger to the KPAS-S system.

192

193 Please insert Figure one about here

194

195 **Statistical Analysis**
196 Descriptive statistics are reported as mean ± SD for normally distributed continuous variables
197 and frequency (%) for categorical variables. Normality was checked using histograms, normal Q-
198 Q plots and the Shapiro-Wilk test. A principal component analysis (PCA) was used to identify
199 optimal sets of key performance indicators on the 46 jump variables extracted from ForceDecks
200 force platform (ForceDecks, London, United Kingdom). This method has been used in previous
201 studies that sought to identify kinematic and kinetic predictors of athletic performance from a
202 number of highly interrelated vertical jump performance measures (Kollias et al. 2001; Laffaye
203 et al. 2007). A second PCA was conducted to explore the reduced dataset of 32 jump
204 performance variables and identify the principal components (PC) summarising the primary
205 force-time variables. The decision on a suitable number of PCs to retain in each PCA required
206 eigenvalues of 1.0 or greater (Kaiser criterion) and was supported using a scree plot.

207

208 Multiple linear regression models using a stepwise regression method were initially performed to
209 identify the potential predictors of the outcome variables of time (s) to 5 m and 15 m. Analyses
210 were carried out on the entire dataset, and also on the data split by sex. Second order polynomial
211 models were also investigated, as visual inspection identified that these quadratic models better
212 matched the data for males than the linear models, with this also confirmed by significantly
213 higher R^2 for the quadratic models (Bobrovitz & Ottenbacher 1998; Park et al. 1990).
214 Collinearity diagnostics were used to avoid the problem of multicollinearity. The assumptions of
215 normality, linearity and homoscedasticity of residuals were verified. Results of the regression
216 modelling are presented in terms of unstandardized coefficients, the 95% CI and p-values, along
217 with the R^2 and standard error of estimate. Data were analysed with statistical software R version

218 3.5.3 and SPSS version 23.0.0 (SPSS Inc., Chicago, IL). P-values less than 0.05 were deemed to
219 indicate statistical significance.

220

Results

222 Seventy-two swimmers, comprising 38 males and 34 females were included in this study. The
223 physical characteristics of the participants are described in Table 1. Out of the 72 participants, 50
224 participants performed the swim start using the front crawl technique, with an additional 12
225 participants performing butterfly and 10 participants using breaststroke. Statistically significant
226 differences among males and females were observed in a number of variables (Table 1), with
227 males significantly heavier, taller and faster to 5 m and 15 m than females.

228

229 Please insert Table one about here

230

231 In the first PCA analysis on the 46 jump variables extracted from ForceDecks force platform
232 (ForceDecks, London, United Kingdom), four PCs which explained 82% of the variance were
233 identified. Thirty-two most influential jump variables were identified from this initial PCA. A
234 secondary PCA was run to explore the new dataset of 32 jump performance variables. The first
235 three components, which explained 93% of the variance, were retained. From this set, 15
236 variables were identified as potential predictors in subsequent regression models (Table 2). The
237 results revealed that Component 1 accounting for 67.5% of the variance, was of predominantly
238 kinetic component. Component 2 accounting for 17.1% of the variation, was predominantly a
239 time-dependent kinematic component. Lastly, Component 3 accounted for 8.5% of the variation,
240 with the highest load attributed to bodyweight.

241

242 Please insert Table two about here

243

244 Linear stepwise multiple regression analyses were performed using the ForceDecks SJ data to
245 predict time to 5 m (see Fig. 2 and Table 3) and time to 15 m (see Fig. 3 and Table 4) in the
246 overall sample of males and females as well as male and female subgroups.

247
248 **Time to 5 m**

249

250 Please insert Figure two about here

251

252

253 The scatterplot in Fig. 2 shows a quadratic relationship between SJ concentric impulse and time
254 to 5 m in males ($R^2 = 0.693$). For a fast time to 5 m for males, visual inspection of the data
255 suggests a minimum concentric impulse production of around 180–200 N.s is required. While
256 visual inspection of the model suggested no additional reduction in time to 5 m with a higher
257 concentric impulse for most swimmers, there are some outlier individuals who appear to derive
258 additional performance benefit from an increased concentric impulse up to approximately 230

259 N.s. The relationship between concentric impulse and time to 5 m observed in females was linear
260 ($R^2 = 0.487$), but this relationship was affected by other factors outlined in Table 3.
261

262 Please insert Table three about here

263

264 Concentric impulse was a statistically significant predictor in all three regression models (Table
265 3). The best prediction equations for time to 5 m in females and males were as follows:

266 Females: T5 m (s) = 2.103 – 0.003 (concentric impulse) – 0.209 (RSImod) + 0.0002 (concentric
267 mean power)

268 Males: T5 m (s) = 2.645 – 0.010 (concentric impulse) + 0.00002 (concentric impulse)^2

269

270 **Time to 15 m**

271
272 Please insert Figure three about here

273

274 The scatterplot in Fig. 3 shows a quadratic relationship between SJ concentric impulse and time
275 to 15 m in males ($R^2 = 0.746$). For a fast time to 15 m in males, a minimum concentric impulse
276 production of around 230 N.s is required. However, similar to Fig. 2, the relationship between
277 concentric impulse and time to 15 m observed in females was linear ($R^2 = 0.651$) but this
278 relationship was also affected by other factors presented in Table 4.

279

280 Please insert Table four about here

281

282 The SJ concentric impulse was also the main significant predictor in all three regression models
283 of the time to 15 m (Table 4). The best regression models were as follows:

284 Females: T15 m (s) = 9.303 – 0.030 (concentric impulse) + 0.035 (body mass) + 0.0002
285 (concentric RPD) – 1.714 (RSImod)
286
287 Males: T15 m (s) = 11.188 – 0.033 (concentric impulse) – 0.048 (age) + 0.00007 (concentric
288 impulse)^2

289

290 **Discussion**

291 The present study revealed that several lower body force-time characteristics, in particular
292 concentric impulse, were significantly related to swim start performance in national and
293 international level swimmers. However, when these analyses were performed for each sex
294 individually, several differences in the prediction of swim start performance were observed.

295 These sex-related differences in key force-time characteristics suggest that strength and
296 conditioning programs and regular monitoring of performance may need to be tailored to male
297 and female swimmers.

298 In the swim start, swimmers have to apply large forces rapidly on the start block to maximise
299 horizontal take-off velocity, which in turn allows them to travel farther horizontally in the air
300 before entering the water (Rebutini et al. 2014). This task demand is consistent with the impulse-
301 momentum relationship, whereby an impulse (the product of force and time of force application)
302 needs to be generated to cause a change in momentum (i.e. velocity) of the system (Schilling et
303 al. 2008). An analysis by Tor et al. (2015a) of the above water parameters in the swim start have
304 found that take-off velocity and time on block were key predictors of swim start performance as
305 assessed by time to 15 m using the OSB11 start block. Strong positive correlations between peak
306 forces in the countermovement jump and peak forces on the OSB11 start block have also been
307 reported by Cossor and colleagues (Cossor et al. 2011). Thus, to be able to achieve a high take-
308 off velocity, a swimmer needs to be able to apply high forces/ impulses off the starting block.
309 Given that the swim start is mainly a concentric only movement, the findings of the present study
310 further emphasise the important association between a swimmers' ability to produce impulse in
311 the SJ and swim start performance.

312 It was expected that the current study would demonstrate a stronger prediction to 5 m than 15 m
313 in the swim start. This hypothesis was based on how the movement pattern in the SJ is similar to
314 the initial push-off in the block phase as well as the findings of Garcia-Ramos et al. (2016b) and
315 Benjanuvatra et al. (2007), who reported a significant correlation in take-off velocity (Garcia-
316 Ramos et al. 2016b) and jump height (Benjanuvatra et al. 2007) in the SJ to 5 m (r =-0.56 and r
317 =-0.92 respectively) but not 15 m. In contrast to this initial hypothesis, the current study
318 demonstrated that the SJ force-time variables explained a greater amount of variance in time to
319 15 m than time to 5 m. Results of the current study were also consistent with Garcia-Ramos et al.
320 (2016a) who observed that the correlations between jump height and swim start performance
321 were greater for the time to 15 m (r = -0.67) than time to 5 m (r =-0.55) using the kick start
322 technique. Such equivalence in the literature was surprising, but it is possible that these
323 contrasting findings from the current study to the limited literature could be attributed to a
324 variety of between study differences, including the swim start technique and start block, as well
325 as the sample size and homogeneity of participants included in the previously published studies.
326 The current study utilised the kick start technique on the OSB11 start block, whereas
327 Benjanuvatra et al. (2007) and Garcia-Ramos et al. (2016b) utilised the grab start and track start,
328 respectively. In addition, both of these studies included only female swimmers and had
329 substantially smaller sample sizes (n = 20 and n = 7), whereas the current study utilised a mix of
330 male and female swimmers, with a larger sample size for both time to 5 m (n = 72) and 15 m (n
331 = 50). As previously mentioned, the underwater phase is a key parameter in swim start
332 performance, as a swimmer spends the highest percentage of the start in the underwater phase for
333 all swim strokes (Cossor & Mason 2001; Tor et al. 2015a; Vantorre et al. 2010). Garcia-Ramos
334 et al. (2016b) have suggested that swimmers require high levels of lower body strength and
335 power to maximise their underwater kick performance. Therefore, it is possible that the stronger
336 prediction in time to 15 m than 5 m in this study and the study by Garcia-Ramos et al. (2016a)
337 may reflect the commonality in lower body force-time characteristics required for the block
338 phase with the kick start technique and the undulatory kicks performed during the underwater
339 phase.

340   Another focus of this study was examining potential sex-related differences in the force-time
341   characteristics that may underpin swim start performance in high-performance swimmers. While
342   concentric impulse was the strongest predictor for time to 5 m and 15 m in both males and
343   females, the current study identified some differences between the sexes with respect to the
344   predictors of time to 5 m and 15 m. For a quick time to 5 m and 15 m in males, a minimum
345   concentric impulse of 200–230 N.s appears required, with any additional impulse production not
346   being associated with a reduction in swim start times for most male swimmers. However, it is
347   worth noting that within the dataset, there appear to be some athletes whose performance sits
348   outside the generalised trend, showing increased performance gains from additional concentric
349   impulse about the level at which most individuals are deriving no further benefit (Fig. 2 and 3).
350   Nevertheless, these findings tend to suggest that for male swimmers capable of producing greater
351   than 230 N.s of impulse, it might be most beneficial for their strength and conditioning program
352   to focus on improving their rate of force development, as it is possible that developing this high
353   level of impulse in a shorter block time is required to further improve their swim start
354   performance.

355   In contrast to the results for the male swimmers, which had concentric impulse as the sole
356   contributing force-time variable from squat jumps, the swim start performance to 5 m and 15 m
357   for females were also influenced by other factors such as RSImod, mean power and concentric
358   RPD. A few possible explanations for the differing strategies could be attributed to maximal
359   strength capacity, load-velocity and neuromuscular capability between both sexes. Although
360   lower body muscular strength was not measured in the current study, maximal strength has been
361   shown to be a limiting factor in jumping ability and other lower body measure of explosive
362   strength (Andersen & Aagaard 2006; Suchomel et al. 2018). Previous research has demonstrated
363   that males possess greater maximal strength and ability to produce greater velocities at the same
364   percentage of one repetition maximum than their female counterparts (Sole et al. 2018; Torrejon
365   et al. 2019). When comparing the force-time curves in the countermovement jump between
366   sexes, previous research has reported that the male and female differences in countermovement
367   jump height were attributed to force characteristics and not temporal characteristics of the force-
368   time curve (Beckham et al. 2019; Sole et al. 2018). This suggests that both sexes possess similar
369   abilities to express forces, but the primary difference in jumping ability was due to the rate and
370   magnitude of force production during both peak eccentric and concentric force production,
371   which may be explained by differences in muscle architecture and structure, such as thickness
372   and size of muscle fibers (Laffaye et al. 2014). These sex related differences might therefore
373   explain some of the differing swim start predictors identified in the present study.

374   Previous studies have suggested that there is a trade-off between time spent on the starting block
375   and take-off velocity, as the likelihood of greater impulses being produced with greater block
376   times (Breed & McElroy 2000; Takeda et al. 2017; Vantorre et al. 2014). From a practical
377   standpoint, a possible strategy to increase impulse generated on the starting block without
378   excessively increasing the time of force application is to increase muscular strength and rate of
379   force development qualities of the lower body through heavy resistance training, ballistic
380   concentric-dominant exercises (i.e. jumps without a preceding eccentric contraction) and
381   plyometric training (Aagaard et al. 2002; West et al. 2011). Heavy resistance training has been
382   shown to increase power production, rate of power development, rate of force development and
383   increases in muscle fiber cross-sectional area and neuromuscular activity (Jakobsen et al. 2012).
384   Ballistic/ plyometric training may improve the transfer of maximal strength to power production

385 and rate of force development (Suchomel et al. 2018), thereby significantly improving swim start
386 performance metrics including time to 5 m, take-off velocity and impulse (Bishop et al. 2009;
387 Rebutini et al. 2014; Rejman et al. 2017). From a monitoring perspective, if a swimmer
388 possesses the concentric impulse production required but has slow start times to 5 m and 15 m,
389 improving rate force development and/or assessing technical factors such as angle of entry,
390 degree of streamline, hydrodynamic drag and underwater propulsion may be imperative to
391 maximise strength transfer to the swim start and ultimately swimming performance (Vantorre et
392 al. 2014). Thus, swimmers should be concurrently performing lower body strength and
393 conditioning program that includes some mixture of strength, ballistic and/or power training
394 while ensuring sufficient practice of the swim start to optimise the transfer of their strength and
395 conditioning program in improving swim start performance (Breed & Young 2003).

396 There are some limitations in this study that could be addressed in future research. Firstly,
397 baseline strength was not measured in any of the participants. Future work should examine the
398 relationship between lower body force-time characteristics in strength matched swimmers and its
399 effect on swim start performance to elucidate if differences between male and female swimmers
400 were due to muscular strength or neuromuscular differences (Nimphius 2019). Secondly, due to
401 the difference in sample sizes for the different swim strokes in the current study, it would be
402 worth exploring what force-time characteristics underpin swim start performance in other swim
403 strokes in comparison to the front crawl, and if there are different neuromuscular qualities
404 required for swim start performance in the different swim strokes.

405 **Conclusion**

406 In summary, this study has identified bodyweight squat jump concentric impulse as a key lower
407 body force-time characteristic that was significantly related to swim start performance in high-
408 performance swimmers. As impulse is the product of the ground reaction force and time of force
409 application, it is integral for a swimmer to have the requisite ability to generate a high level of
410 concentric impulse in a relatively short amount of time. Due to the different strength of the
411 prediction equations, it appears that male and female swimmers utilise somewhat differing
412 strategies during the swim start. While it is unknown if this is predominantly a result of the
413 differences in muscular strength and force producing capacity between sexes, our results
414 highlight the need for strength and conditioning coaches to consider individualising training
415 programs to enhance swim start performance and ultimately swimming performance between
416 sexes.

417

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542

Figure 1

Overview of the camera set-up and instrumented starting block (Kistler Group, 2019).

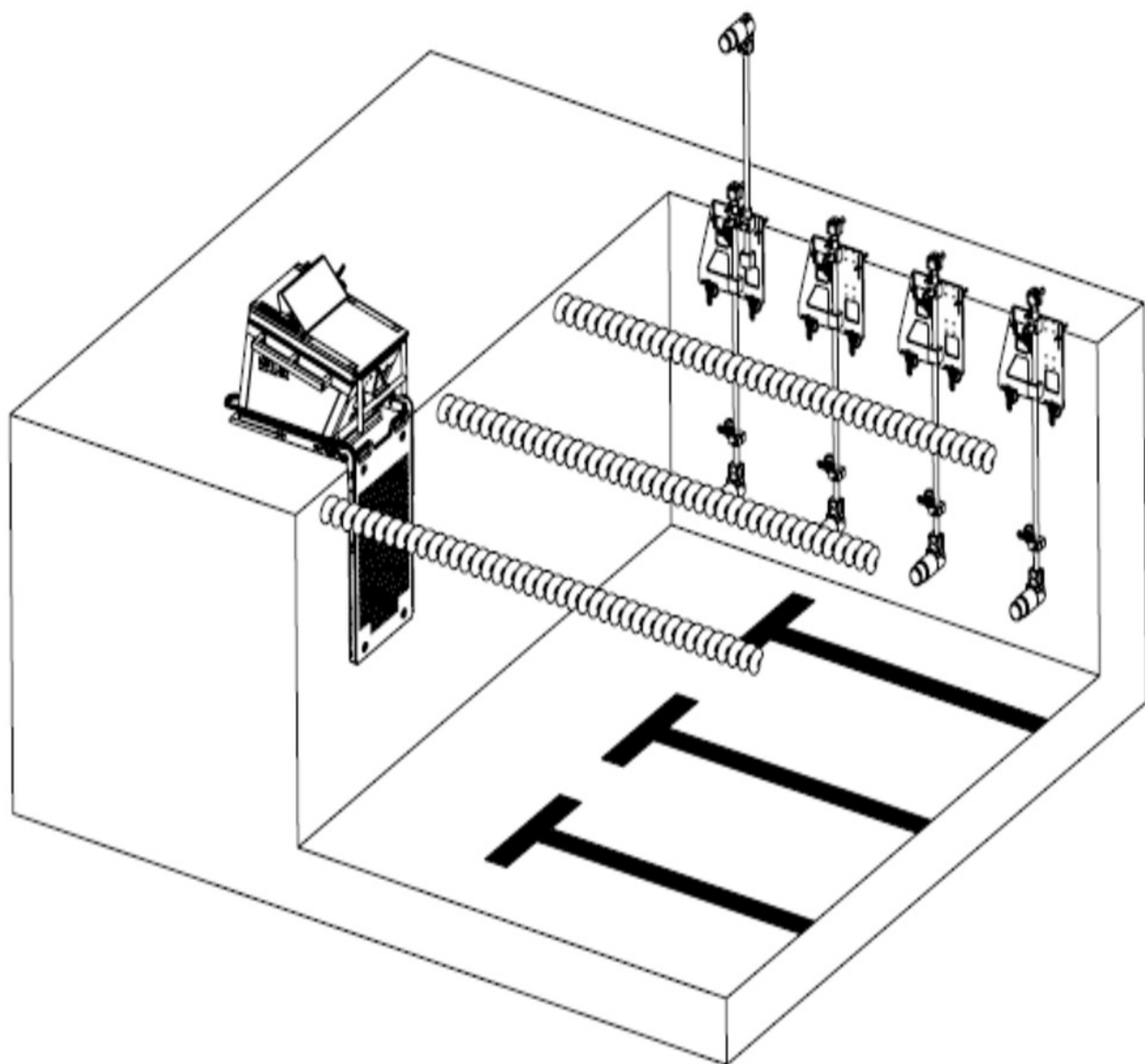



Figure 2

Relationship between concentric impulse (N.s) against time to 5 m (s) across females and males. Poly means polynomial regression to order 2, i.e. quadratic.

The grey dotted line and diamond markers represent the linear relationship between concentric impulse (N.s) and time to 5 m in females. The dashed line with circle markers represents the quadratic relationship between concentric impulse (N.s) and time to 5 m in males.

Figure showing scatter plot of Time to 5 m (s) versus Concentric Impulse (N.s) with $R^2 = 0.487$ and $R^2 = 0.693$.

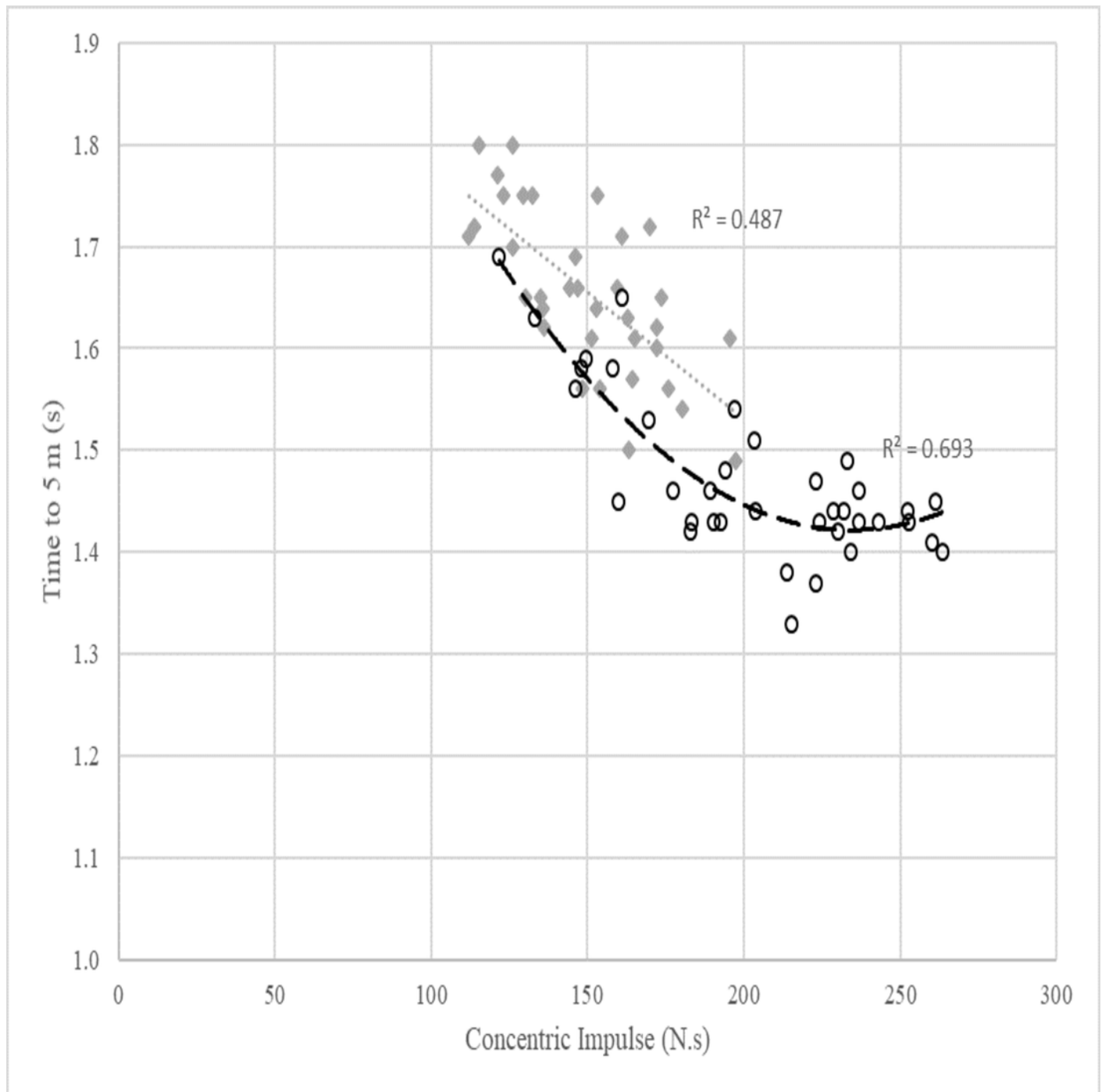



Figure 3

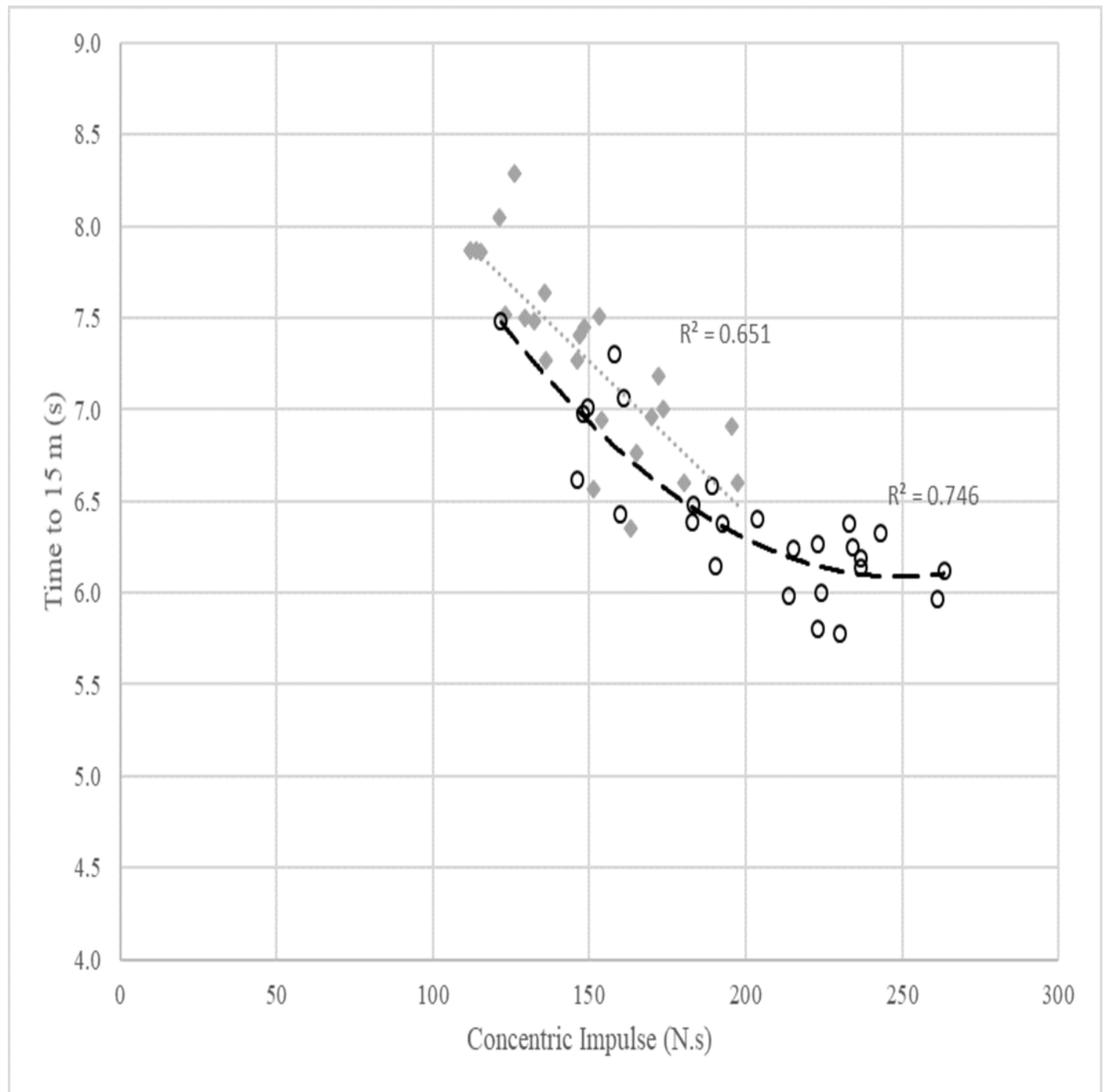
Relationship between concentric impulse (N.s) against time to 15 m (s) across females and males. Poly means polynomial regression to order 2, i.e. quadratic.

The grey dotted line and diamond markers represent the linear relationship between concentric impulse (N.s) and time to 15 m in females. The dashed line with circle markers represents the quadratic relationship between concentric impulse (N.s) and time to 15 m in males.

R² = 0.651

R² = 0.746

Time to 15 m (s)

Concentric Impulse (N.s)

Physical characteristics of participants.

All data is presented as means and standard deviations. *$p< 0.05$; **$p< 0.001$ between males and females.

Variables	Males		Females	
	5 m ($n = 38$)	15 m ($n = 26$)	5 m ($n = 34$)	15 m ($n = 24$)
Age (years)	21.0 ± 3.1	21.2 ± 3.2*	20.1 ± 3.2	19.2 ± 3.2
Body mass (kg)	76.7 ± 10.2**	76.5 ± 11.0**	64.8 ± 8.4	64.2 ± 8.4
Height (m)	1.83 ± 0.08**	1.85 ± 0.08**	1.73 ± 0.06	1.73 ± 0.06
Time to 5 m (s)	1.48 ± 0.09**		1.65 ± 0.08	
Time to 15 m (s)		6.4 ± 0.44**		7.3 ± 0.5

List of 15 most influential potential predictors of swim start performance identified from the PCA and their correlations with the principal components.

Potential predictors	Principal Component		
	PC1	PC2	PC3
Variation explained for each component	**67.5 %**	**17.1 %**	**8.5 %**
Bodyweight (BW)	-0.71	0.11	0.68
Concentric impulse	-0.88	0.31	0.34
Concentric mean force	-0.91	-0.09	0.39
Concentric mean power	-0.94	0.13	0.14
Concentric peak force	-0.92	-0.15	0.32
Concentric rate of power development (RPD)	-0.93	-0.31	0.04
Force at peak power	-0.92	-0.05	0.33
Peak power	-0.95	0.24	0.14
Reactive strength index modified (RSImod)	-0.90	-0.12	-0.20
Take-off peak force	-0.92	-0.15	0.32
Concentric peak velocity	-0.77	0.55	-0.29
Concentric rate of force development (RFD) BW	-0.59	-0.75	-0.15
Concentric RFD	-0.72	-0.66	0.05
Jump height (impulse-momentum)	-0.75	0.56	-0.31
Velocity at peak power	-0.68	0.66	-0.27

Multiple linear regression models to predict swim start time (s) to 5 m performance in females, males and both females and males combined.

		% contribution	Beta coefficient (95% CI)	p-value
All	**Concentric Impulse (N.s)**	70.4	-0.002 (-0.002 to -0.001)	< 0.001
	Sex (Females)	5.4	0.065 (0.028 to 0.102)	0.001
	RSImod (m/s)	1.5	-0.084 (-0.164 to -0.004)	0.040
	Constant		1.882 (1.790 to 1.974)	< 0.001
	***R²* (SEE)**		0.773 (0.059)	
Females	**Concentric Impulse (N.s)**	51.6	-0.003 (-0.004 to -0.002)	< 0.001
	RSImod (m/s)	9.5	-0.209 (-0.315 to -0.104)	< 0.001
	Concentric Mean Power (W)	7.8	0.0002 (0.00004 to 0.0003)	0.010
	Constant		2.103 (1.986 to 2.219)	< 0.001
	***R²* (SEE)**		0.689 (0.047)	
Males	**Concentric Impulse (N.s)**	53.6	-0.010 (-0.015 to -0.005)	< 0.001
	Concentric Impulse² (N.s)²	12.3	0.00002 (0.00001 to 0.00003)	0.001
	Constant		2.645 (2.167 to 3.124)	< 0.001
	***R²* (SEE)**		0.659 (0.055)	

1   SEE = standard error of estimate

Multiple linear regression models to predict swim start time (s) to 15 m performance in females, males and both females and males combined.

		% contribution	Beta coefficient (95% CI)	p value
All	**Concentric Impulse (N.s)**	76.1	-0.008 (-0.011 to -0.004)	< 0.001
	Age (years)	3.5	-0.052 (-0.087 to -0.018)	0.004
	Sex (female)	3.0	0.362 (0.151 to 0.572)	0.001
	Constant		9.074 (8.503 to 9.646)	< 0.001
	R^2 (SEE)		0.826 (0.278)	
Females	**Concentric Impulse (N.s)**	65.1	-0.030 (-0.041 to -0.020)	< 0.001
	Body mass (kg)	9.3	0.035 (0.006 to 0.064)	0.020
	Concentric RPD (W/s)	4.9	0.0002 (0. 00006 to 0.0003)	0.004
	RSImod (m/s)	4.8	-1.714 (-3.215 to -0.213)	0.027
	Constant		9.303 (8.398 to 10.208)	< 0.001
	R^2 (SEE)		0.841 (0.225)	
Males	**Concentric Impulse (N.s)**	66.6	-0.033 (-0.058 to -0.008)	0.011
	Age (years)	9.4	-0.048 (-0.086 to -0.010)	0.016
	Concentric Impulse^2 (N.s)^2	4.7	0.00007 (0.000007 to 0.0001)	0.031
	Constant		11.188 (8.975 to 13.401)	< 0.001
	R^2 (SEE)		0.807 (0.205)	

1   SEE = standard error of estimate