

Association Between Measures of Maximal and Rapid Force Production with Rowing Ergometer Performance in Adolescent Male Rowers

Authors:

Steven House^{1,2}, Alex Wolf^{3,4}, Anthony Turner¹ and Chris Bishop¹

Affiliations:

1. London Sport Institute, Faculty of Science and Technology, Middlesex University, London, UK
2. Performance Herts, University of Hertfordshire, Hatfield, UK
3. Science of Rowing LLC, Wichita, Kansas, USA
4. Strength and Conditioning Academy Ltd, London, UK

Correspondence:

Name: Chris Bishop

Email: C.Bishop@mdx.ac.uk

Address: As above for affiliation 1.

ABSTRACT

The aim of the present study was to better understand the associations between maximal and rapid force production measures, and rowing ergometer performance in youth male rowers. Twenty-three junior male rowers (9 mid-late pubescent, 14 post pubescent, mean age: 14.89 ± 0.60 years) volunteered to participate. For maximal and rapid force production measures, assessments included: i) isometric mid-thigh pull [IMTP], ii) isometric hip thrust, and iii) countermovement jump [CMJ]. Rowing performance was determined from a 6-stroke peak power test and 2-km time trial. Pearson's r correlation coefficients were used to analyse relationships between physical test measures and rowing performance, with statistical significance set at $p \leq 0.0036$ once a Bonferroni correction had been applied. Results showed CMJ net impulse to have a very large relationship with all rowing ergometer performance measures (power output and time). In addition, multiple isometric force production measures also exhibited large to very large correlations with rowing ergometer performance. The findings of this study suggest practitioners should look to enhance both maximal and rapid force production measures when aiming to improve junior male rowing ergometer performance. However, caution should be taken when assessing and using some early force-time data from isometric test protocols, owing to elevated variability.

Key Words: Countermovement Jump; Isometric Mid-Thigh Pull; Isometric Hip Thrust; Youth.

19 INTRODUCTION

20 Rowing requires athletes to have high levels of maximal and rate of force production capabilities, and
21 be both aerobic and anaerobically fit to succeed (46). For the most part, a rower's success is
22 determined by their ability to produce and maintain superior impulse over their competitors (27).
23 Typically, 210-230 rowing strokes are performed over a 2 km race; with boat type, individual, and
24 environmental factors influencing race times, which often last 5.5-7 minutes in duration (3,27). During
25 a 2 km single scull race (the slowest of the boat categories), scullers typically average 33 strokes per
26 minute with a drive phase of up to 0.9 s – although the faster the athlete, the quicker the drive phase
27 and higher the stroke rate (47). However, obtaining on-water data is not always feasible, affordable,
28 or reliable, which has resulted in the mass increase in perceived utility of rowing ergometers, for both
29 non-elite and elite rowers (22). Consequently, individual's time trial speed and average power output
30 are regularly assessed via rowing ergometers during training and testing (48). These allow for
31 environmentally controlled and reliable measures to be tracked, given the inherent challenges of
32 gathering on-water measures (45,50).

33 The rowing stroke can be described as a long-front-loaded leg-driven stroke and consists of two
34 interconnected phases: i) the recovery, and ii) the drive phase (56). The recovery phase starts at the
35 end of the drive phase, and is initiated by the rockover (a movement where the rower shifts their
36 weight from the back of the seat to the front of the seat, by moving from the hips and pelvis) (40),
37 characterised by elbow extension, shoulder flexion, and hip flexion. At the start of the recovery, a
38 lateral view of the rockover position would demonstrate the shoulders positioned anterior to the hips
39 with knees still extended. The rower begins to flex the knees (while maintaining the rockover), until in
40 the catch position. Once in the catch position, the hips, knees, and ankles are in near full flexion, with
41 the shoulders still positioned anterior to the hips, accompanied by elbow extension and shoulder
42 flexion (46). The catch position represents the transition between the end of the recovery phase and
43 start of the drive phase, which focuses on propulsive force production (40). The drive phase is initiated

by knee extension with the rower still maintaining the shoulders positioned anterior to the hips, elbow extension, and shoulder flexion (40). The knee extensors (quadriceps) are the primary musculature involved in propulsive force production during the early drive phase (54). During the latter stages of the drive phase, the knees continue to fully extend with the hips also extending due to force production contributions from the gluteus maximus and adductor magnus muscles (17). Importantly though, the gluteus maximus plays a more prominent role in force production during terminal hip extension, which is not achieved during the rowing stroke. In contrast, peak force is typically observed in the early-mid drive phase (40), highlighting the critical role of the quadriceps and adductor magnus muscles for rowers. The trunk moves from the rockover to the layback position, with shoulders positioned posteriorly to the hips, and the posterior trunk continuing to contribute to propulsive force production (40). Only once in the layback position, the elbows begin to flex and shoulders extend, pulling the oar handle into the chest. Collectively, owing to large amounts of force production during the drive phase coming from the quadriceps and gluteal complex, assessment protocols involving these muscle groups are relevant, which has been supported in previous associative investigations (1,14,25,31).

Previous research has reported significant small to large correlations between strength test metrics and rowing ergometer performance ($r = 0.40$ to 0.94 , $p < 0.05$). These tests include: 1RM (repetition maximum) leg press (1,25), 1RM hang or power cleans (14,29), 1RM squat (14), 1RM bench pull (1), isokinetic dynamometer leg extension (43), and peak force during the following isometric assessments: trunk extension, trunk flexion, leg press, and mid-thigh pull (31). It has been suggested that isometric multi-joint tests are the most appropriate method for assessing athletes maximal and rapid force development capabilities (9). This is because these are considered less fatiguing compared to maximal dynamic strength tests, allow for multiple metrics to be quantified, are considered time efficient, reliable, and able to distinguish between individuals' maximal force production capabilities (18). Therefore, assessments which target musculature associated with rowing power development and transfer are deemed most appropriate (i.e. quadriceps, the posterior chain complex, and the trunk

musculature) (30,49). With this in mind, assessments such as the isometric mid-thigh pull [IMTP] and CMJ, to name just a couple, are likely to be valid, reliable, and appropriate assessment protocols for practitioners working with rowing athletes.

Gee et al. (15) conducted a survey to collect information regarding the strength and conditioning practises of rowing programmes in the United Kingdom. The findings showed that ~50% of practitioners included plyometrics and ballistic type training methods in their strength and conditioning programmes. These methods involve continually accelerating throughout an exercise, resulting in the projection of the athlete or equipment with maximal intent (11). These methods seem appropriate given previous research has shown that the rowing stroke is indicative of slow stretch-shortening cycle mechanics (20). Previous associative analysis has shown very large relationships between CMJ height and 2 km rowing ergometer performance ($r = -0.74$) (25), with similar findings reported between these two assessments elsewhere ($r = 0.56$) (39). Both the aforementioned studies reported only jump height, which although useful, provides no understanding as to how the outcome measure was obtained. Examining the association between rowing performance and other jump metrics seems like a logical line of enquiry, given this has been rarely investigated in the available body of evidence for rowing.

Additionally, Ledergerber et al. (31) assessed explosive force development via rate of force development (RFD) metrics calculated during the isometric leg press and IMTP. To the authors knowledge, this is the only previously published study examining the associations between explosive force development measured in an isometric protocol and rowing ergometer performance. The findings suggested that there was a significant correlation with ergometer performance and RFD over 150 ms ($r = -0.69$, $p < 0.05$) and 350 ms ($r = -0.79$, $p < 0.05$) in the isometric leg press, in addition to RFD over 300 ms during the IMTP ($r = -0.81$, $p < 0.05$) (31). Importantly though, the reliability data via intraclass correlation coefficients (ICC) for these RFD measures ranged from 0.61-0.78, highlighting some questionable inconsistencies in these measures. Furthermore, these findings were from a small

sample size ($n = 14$); thus, hard to generalise within the wider rowing population (31). However, recent literature has suggested that if rapid force production is of interest, practitioners may wish to consider force at specific time points on the force-time curve (i.e., force at 100, 150, 200 ms, etc.) (10), given these measures may be more reliable than measuring RFD (i.e., the change in force divided by the change in a given time epoch), as per the methods of Ledergerber et al. (31). To the best of the authors knowledge, the reliability and potential associations of force at specific time-points have not previously been researched within the context of rowing performance. Consequently, the primary purpose of this study was to better understand the associations that specific measures of maximal and rapid force production may have with rowing ergometer performance in male adolescent rowers.

METHODS

Experimental Approach to the Problem

A cross-sectional study design was adopted to assess the associations between specific measures of maximal and rapid force production with rowing ergometer performance. Two data collection sessions occurred; the first involving the maximal and ballistic force production assessments, and the second for the rowing ergometer testing. Testing sessions were 72-hours apart and given the familiarity of strength training and testing with the youth rowing population who volunteered for the present investigation, no familiarization was deemed necessary; only a thorough warm-up protocol (outlined in the procedures section).

Subjects

Twenty-three junior male rowers (age: 14.89 ± 0.60 years; height: 174.87 ± 9.52 cm; body mass: 66.78 ± 13.96 kg) volunteered to participate in the study. A minimum of 21 participants was determined

from a priori power analysis using G*Power (Version 3.1, University of Dusseldorf, Germany) implementing statistical power of 0.8, a type 1 alpha level of 0.05, and an effect size of 0.5. The Khamis-Roche method estimated the participants predicted adult height (PAH) (26,44). Subsequently, current height was reported as a percentage of PAH which enabled the data to be grouped relative to individual's maturation (35). Inclusion criteria required all rowers to have trained and competed regularly for at least two years prior to data collection, in line with previous research in this population (36). In addition, all subjects had a minimum of one year's experience of structured strength and conditioning training, and were healthy and injury free at the time of testing. Given the age of the participant group, written informed consent was provided by parents or legal guardians, in addition to participant ascent. Ethical approval was granted from the London Sport Institute research and ethics committee at Middlesex University, London, UK (Application number: 28158).

Procedures

Warm-Up

All participants initially started with a standardised warm-up consisting of 5-minutes steady state rowing (with instructions to row at 50-60% of perceived maximal effort speed for that duration). Following this, a series of dynamic stretches were performed and consisted of: the 'crucifix' (5 each side), 'inchworms' (8 repetitions), 'world's greatest stretch' (8 each side), body weight good mornings (10 repetitions), and forward lunges with a twist (6 each side). Further to this, the final component of the warm-up was to perform body weight CMJ's (1 set of 3 repetitions) at 50, 75 and 100% of perceived maximal effort. Following the warm-up, athletes executed each testing protocol in the order listed below. This was done to minimise any potential fatiguing effect on subsequent tests. For the isometric protocols, practice trials at 50, 75 and 100% of perceived maximal effort were also

implemented, prior to data collection. The mean score from all data collection trials was used for subsequent data analysis.

Countermovement Jump (CMJ)

The CMJ testing required each participant to jump with their hands on their hips for the entire duration of the jump (38). The test started with the participant standing upright, subsequently descending by flexing at the ankles, knees and hips, to a self-selected depth. Immediately following the descent, the ankles, knees and hips rapidly extended, with all participants given specific instructions to “jump as high as you can”. Jumps were recorded via the use of slow-motion video capture at 240 frames per second, and later analysed through the My Jump Lab Application, on an iPhone 15pro running IOS 17.4 (Apple inc., USA). The following metrics were obtained, jump height (m), time to take-off (s) and RSI modified, with the latter two metrics recently validated (4). Net impulse was also determined via inverse dynamics, by calculating take-off velocity from jump height, then multiplying it by body mass (55).

- Step 1: Take-off velocity (m.s^{-1}) = $\sqrt{\text{jump height (m)} * (2 * 9.81)}$
- Step 2: Net impulse (N.s) = mass (kg) * take-off velocity (m.s^{-1})

Isometric Mid-Thigh Pull (IMTP)

The IMTP involved setting up with a hip angle between 140-150° and knee angles between 125-145°, in line with previous technical model suggestions (9). This protocol measured force-time data via the Force Hooks 2 product (Ascend Labs., AUS). From this force-time data, the following metrics were extracted: peak force, force at 100 ms, 200 ms and 300 ms, all recorded in Newtons (N). These metrics were determined via the use of custom analysis in MATLAB software (R2022a; MathWorks, Natick,

MA, USA). The initiation of each trial was determined by surpassing a 20 N threshold. Rowers were instructed to “push into the ground as hard and as fast as possible” without any countermovement in order to achieve valid measures of both peak force and time-specific measures of force (19,34). Each trial started with the instruction: “3, 2, 1, pull” with the participants receiving loud verbal encouragement throughout the repetition until the force trace plateaued in line with previous protocols and recommendations (9,31).

Isometric Hip Thrust (IHT)

The IHT test was used to measure maximal force production capability of the hip extensors. This was a somewhat novel test to undertake in a rowing population, although peak force has also been measured in a similar protocol previously and reported to produce reliable data (16). The internal hip angle was set to 130°, the same orientation as the 50° calculated in the study by Goodwin and Bull (16), with this particular set up reported to produce the greatest peak force (16). Specifically, the thoracic spine was positioned on a bench, the barbell in the inguinal crease, the feet flat, and shins vertical (when in contact with the bar) (5). The instructions were to: “push as hard and as fast as possible.” The barbell was fixed within the Force Hooks 2 (Ascend Labs., AUS). There was a barbell pad placed between the athlete and the bar for comfort. The athletes were instructed to close the gap between the bar pad and hip prior to each trial. Technical coaching cues were supplied to reinforce correct execution if needed (e.g., “brace the trunk” and “push into the floor”). Each trial lasted 3-seconds and began with a “3, 2, 1, push” instructions, with verbal encouragement provided in a comparable format as the IMTP protocol. The metrics extracted from subsequently analysed force-time data were: peak force, force at 100 ms, 200 ms, and 300 ms, all recorded in Newtons (N). Again, these metrics were determined via custom analysis in the MATLAB software (R2022a; MathWorks, Natick, MA, USA), with the first meaningful change in force again determined by surpassing a 20 N threshold.

189

190 *Rowing Ergometer Peak Stroke Power Test*

191 This test was performed during the second data collection session, before the 2 km ergometer test
192 and as per what has been reported in previous literature (36). The same warm-up protocol, as set out
193 in session one was completed prior to data collection. However, some escalating intensity 6-stroke
194 rowing trials were included in place of warm-up CMJ efforts. The peak stroke power (PSP) test was
195 conducted on a Concept II model D rowing ergometer (Concept2 Inc., Germany). The drag factor was
196 set at 115; as recommended by British Rowing (8) and therefore used by all throughout this study.
197 First, rowers performed six “introductory” strokes, immediately followed by six maximal effort
198 strokes. The following measures were collected: highest external power output, recorded in Watts
199 (W), stroke rate of that specific stroke was also recorded along with both the average stroke power
200 output (W) and the average stroke rate from the six “all-out effort” strokes. Participants performed
201 two PSP trials, each with 5-minutes rest between them. Participants received verbal encouragement
202 during this test and were able to watch the visual display providing feedback throughout.

203

204 *Rowing Ergometer 2 km Time Trial*

205 The 2 km rowing ergometer test is the most well recognised and adopted measure of a rower’s sport-
206 specific capabilities (15). Each athlete performed this time trial on the same rowing ergometer as they
207 undertook the PSP test, with the same aforementioned test set-up. The recorded metrics were: overall
208 average power (W), average strokes per minute, average power over 500 m splits (for each 500 m
209 interval), and overall time (s).

210

211 ***Statistical Analysis***

Descriptive statistics were displayed as means $\pm$ standard deviation (mean $\pm$ SD). All data and statistics were recorded in Microsoft Excel (Microsoft Corp., USA) or SPSS (IBM SPSS Inc., Version 29, USA). All completed test data was assessed for normality via a Shapiro-Wilk test ($p > 0.05$). The reliability of test measures was determined via a two-way random intraclass correlation coefficient (ICC) with absolute agreement and 95% confidence intervals (CI), the coefficient of variation (CV) with 95% CI, and the standard error of the measurement (SEM). The interpretation of the ICC values followed guidelines suggested by Koo and Li (28), where: < 0.5 = poor, $0.5-0.75$ = moderate, $0.76-0.9$ = good and > 0.9 = excellent. CV values were interpreted relative to previously used parameters: poor ($> 10\%$), moderate ($5-10\%$), or good ($< 5\%$) (2). Correlational analysis was assessed via Pearson's r correlations if the data was normally distributed or Spearman's ρ correlations if the data violated the assumption of normality. The Bonferroni correction factor was applied to all correlations to account for multiple comparisons and any potential type-II error, resulting in the statistical significance value being $p < 0.0036$. Correlations were categorised: $0-0.09$ = trivial, $0.1-0.29$ = small, $0.3-0.49$ = moderate, $0.5-0.69$ = large, $0.7-0.89$ = very large, and ≥ 0.9 = nearly perfect (24).

Furthermore, sub-group allocation based on individual maturation was determined. Independent samples t -tests with Hedges g effect size data and 95% CI were calculated to provide an understanding of both statistical and practical significance, when comparing between maturation sub-groups. Hedges g values were interpreted as: $g < 0.35$ = trivial; $0.35-0.80$ = small; $0.81-1.50$ = moderate; and > 1.5 = large (23). Finally, the total score of athleticism (TSA) was also determined and presented in respect to individual maturation status (52). This first involved converting all test data sets into t -scores (as the sample size was below 30 participants) (52). This provided each rower with a composite ranking relative to their peers; thus, providing an understanding of over-arching strengths and weaknesses from a rowing-specific and physical fitness perspective.

RESULTS

Table 1 shows the mean $\pm$ SD, CV, ICC and SEM data for the entire test battery. Within session reliability of test measures ranged between moderate to excellent (ICC = 0.57 to 1.00), with force at 100 ms during the IHT assessment being the only metric to elicit moderate ICC reliability. The CV values ranged from good to poor (CV = 1.29 to 25.42%), with poor CV data shown for force at 100 (13.34%) and 200 ms (13.27%) during the IMTP, and for all IHT rapid force production metrics (CV = 10.72 to 25.42%).

Table 1. Descriptive statistics and within-session reliability for test metrics.

Test	Metric	Mean $\pm$ SD	CV (95%CI)	ICC (95%CI)	SEM
CMJ	Jump Height (m)	0.33 $\pm$ 0.07	2.57 (1.79, 3.35)	0.99 (0.98, 1.00)	0.01
	Time to Take-Off (s)	0.95 $\pm$ 0.19	5.85 (4.07, 7.64)	0.94 (0.85, 0.98)	0.05
	RSI mod	0.37 $\pm$ 0.11	7.28 (5.06, 9.50)	0.96 (0.89, 0.98)	0.02
	Net Impulse (N.s)	169.74 $\pm$ 37.01	1.29 (0.89, 1.68)	1.00 (1.00, 1.00)	2.03
PSP	Peak Power Stroke (W)	406.98 $\pm$ 105.43	1.70 (1.18, 2.22)	1.00 (0.99, 1.00)	6.67
	Peak Power Stroke SPM	45.38 $\pm$ 5.96	2.33 (1.61, 3.04)	0.96 (0.89, 0.98)	1.26
	Average Power (W)	451.46 $\pm$ 122.23	1.31 (0.91, 1.71)	1.00 (0.99, 1.00)	6.70
	Average SPM	47.45 $\pm$ 6.18	2.04 (1.41, 2.67)	0.96 (0.91, 0.98)	1.20
IMTP	Peak Force (N)	1345.37 $\pm$ 384.36	3.75 (2.60, 4.89)	0.99 (0.98, 1.00)	40.31
	Force @ 100 ms (N)	503.19 $\pm$ 182.11	13.34 (9.27, 17.42)	0.89 (0.78, 0.95)	60.67
	Force @ 200 ms (N)	628.50 $\pm$ 261.92	13.27 (9.22, 17.32)	0.93 (0.86, 0.97)	70.28
	Force @ 300 ms (N)	914.94 $\pm$ 257.86	8.52 (5.92, 11.12)	0.94 (0.88, 0.97)	62.10
	Peak Force / Mass (N.kg ⁻¹)	20.05 $\pm$ 3.61	3.75 (2.60, 4.89)	0.97 (0.94, 0.99)	0.64
IHT	Peak Force (N)	1717.82 $\pm$ 549.91	5.67 (3.94, 7.40)	0.98 (0.96, 0.99)	75.80
	Force @ 100 ms (N)	509.93 $\pm$ 200.54	25.42 (17.66, 33.17)	0.57 (0.15, 0.80)	131.35
	Force @ 200 ms (N)	798.89 $\pm$ 274.95	17.24 (11.98, 22.50)	0.78 (0.56, 0.90)	129.55
	Force @ 300 ms (N)	1024.02 $\pm$ 288.02	10.72 (7.45, 14.00)	0.88 (0.77, 0.95)	236.98
	Peak Force / Mass (N.kg ⁻¹)	25.38 $\pm$ 5.28	5.67 (3.94, 7.40)	0.95 (0.90, 0.98)	1.17
2km Ergometer Test	Time (s)	509.83 $\pm$ 61.47	-	-	-
	Overall Mean Power (W)	178.17 $\pm$ 52.48	-	-	-
	Overall Mean SPM	31.13 $\pm$ 4.75	-	-	-
	1st 500m Power (W)	204.39 $\pm$ 57.65	-	-	-
	2nd 500m Power (W)	168.09 $\pm$ 50.99	-	-	-
	3rd 500m Power (W)	165.17 $\pm$ 53.02	-	-	-
	4th 500m Power (W)	181.26 $\pm$ 55.25	-	-	-

CMJ: countermovement jump; PSP: peak stroke power test; IMTP: isometric mid-thigh pull; IHT: isometric hip trust; RSI mod: reactive strength index modified; SPS: strokes per minute; CV: coefficient of variation; ICC: intraclass correlation coefficient; CI: confidence intervals; SEM: standard error of the measurement.

Table 2 shows associations between rowing specific test metrics and the physical fitness performance measures. The correlational analysis showed net impulse from the CMJ protocol had very large positive associations with all performance power measures during both ergometer rowing tests ($r =$

247 0.77 to 0.87, $p < 0.0036$) and very large inverse correlations with 2 km rowing ergometer time ($p = -$
248 0.72, $p < 0.0036$). Additionally, significant large to very large positive correlations were also found
249 between IMTP metrics; peak force and force @ 300 ms and all power measures during both ergometer
250 rowing tests ($r = 0.64$ to 0.84 , $p < 0.0036$). Additionally, significant large to very large inverse
251 correlations were also found between the same IMTP metrics and 2 km rowing ergometer time ($p = -$
252 0.65 to -0.70 , $p < 0.0036$). When considering the IHT, significant large to very large positive correlations
253 were found between peak force, force @ 200 ms and force @ 300 ms with both measures of power
254 in the PSP test ($r = 0.67$ to 0.74 , $p < 0.0036$). Although, only force @ 300 ms presented a significant
255 correlation with any 2 km rowing ergometer measure, a large correlation with the first 500 m average
256 power output ($r = 0.56$, $p < 0.0036$).

Table 2. Relationships between physical performance tests and rowing ergometer test measures.

Peak Stroke Power Rowing Ergometer Test						2km Rowing Ergometer Test						
Test	Metric	Total Average Power	Total Average SPM	Peak Power	Peak Stroke SPM	<u>Total Time</u>	Average Power	<u>Total Average SPM</u>	500 Average Power	1000 Average Power	1500 Average Power	2000 Average Power
IMTP	Peak Force	0.82	-0.07	0.84	0.02	-0.65	0.72	0.23	0.68	0.67	0.69	0.72
	Force @ 100 ms	0.47	0.44	0.41	0.44	-0.49	0.44	0.49	0.47	0.43	0.42	0.39
	<u>Force @ 200 ms</u>	0.56	0.40	0.49	0.43	-0.62	0.63	0.52	0.61	0.52	0.58	0.53
	Force @ 300 ms	0.78	0.08	0.74	0.13	-0.70	0.69	0.17	0.66	0.64	0.65	0.71
	Peak Force/Mass	0.52	0.11	0.53	0.13	-0.37	0.38	0.28	0.38	0.32	0.39	0.40
IHT	Peak Force	0.69	-0.15	0.68	-0.11	-0.42	0.52	0.11	0.54	0.48	0.46	0.54
	Force @ 100 ms	0.49	0.02	0.46	-0.01	-0.34	0.39	0.15	0.46	0.37	0.33	0.38
	Force @ 200 ms	0.70	0.13	0.67	0.12	-0.53	0.53	0.25	0.57	0.51	0.46	0.50
	Force @ 300 ms	0.74	0.07	0.72	0.11	-0.48	0.54	0.17	0.60	0.52	0.45	0.52
	Peak Force/Mass	0.43	0.01	0.41	-0.02	-0.19	0.19	0.20	0.27	0.13	0.13	0.22
CMJ	Jump Height	0.43	0.34	0.37	0.28	-0.34	0.37	0.35	0.47	0.36	0.35	0.31
	Time to Take-Off	-0.17	-0.55	-0.20	-0.55	0.12	-0.12	-0.50	-0.28	-0.10	-0.05	-0.06
	RSI mod	0.34	0.62	0.31	0.57	-0.28	0.27	0.59	0.43	0.26	0.22	0.20
	Net Impulse	0.87	-0.05	0.86	0.02	-0.72	0.83	0.25	0.84	0.81	0.77	0.79

Underlined test metrics indicate non-parametric data so Spearman's rho correlation coefficient was used instead of Pearson correlation coefficient.

***Bold** values indicate a significant correlation with the Bonferroni correction factor applied, significance value of $p < 0.0036$.*

IMTP: isometric mid-thigh pull; IHT: isometric hip thrust; PSP: peak stroke power test; CMJ: countermovement jump; RSI mod: reactive strength index modified; W: watts; Peak Force/Mass: peak force divided by body mass; SD: standard deviation; LL: lower limit; UL: upper limit.

Table 3. Independent group effect sizes for all performance measures.

Test	Metric	Post Maturation	Circa (mid-late) Maturation	Hedges <i>g</i> (95%CI)	Effect Size Descriptor
		Mean $\pm$ SD	Mean $\pm$ SD		
IMTP	Peak Force	1553.87 $\pm$ 303.18	1021.03 $\pm$ 248.46	1.81 (0.75, 2.87)	Large
	Force@100ms	514.06 $\pm$ 170.82	486.28 $\pm$ 197.22	0.15 (-0.74, 1.04)	Trivial
	Force@200ms	667.17 $\pm$ 268.50	568.34 $\pm$ 239.23	0.37 (-0.53, 1.27)	Small
	Force@300ms	1011.66 $\pm$ 231.98	764.48 $\pm$ 221.39	1.04 (0.10, 1.99)	Moderate
	Peak Force/Mass	21.85 $\pm$ 2.67	17.25 $\pm$ 3.06	1.57 (0.55, 2.59)	Large
IHT	Peak Force	1893.88 $\pm$ 480.49	1443.95 $\pm$ 538.94	0.86 (-0.07, 1.79)	Moderate
	Force@100ms	564.14 $\pm$ 217.32	425.60 $\pm$ 132.77	0.70 (-0.21, 1.62)	Small
	Force@200ms	892.44 $\pm$ 275.75	653.36 $\pm$ 200.30	0.92 (-0.01, 1.86)	Moderate
	Force@300ms	1136.17 $\pm$ 249.98	849.58 $\pm$ 254.56	1.10 (0.14, 2.05)	Moderate
	Peak Force/Mass	26.42 $\pm$ 4.33	23.75 $\pm$ 6.15	0.50 (-0.40, 1.41)	Small
2km Ergometer	Total Time	482.90 $\pm$ 34.93	551.71 $\pm$ 69.83	-1.30 (-2.28, -0.32)	Moderate
	AVE Power	198.93 $\pm$ 41.31	145.89 $\pm$ 51.69	1.12 (0.16, 2.08)	Moderate
	Total AVE SPM	30.07 $\pm$ 2.37	32.78 $\pm$ 6.66	-0.58 (-1.49, 0.33)	Small
	500 AVE Power	224.21 $\pm$ 45.05	173.56 $\pm$ 61.43	0.94 (0.00, 1.88)	Moderate
	1000 AVE Power	185.71 $\pm$ 40.16	140.67 $\pm$ 53.85	0.95 (0.01, 1.89)	Moderate
	1500 AVE Power	185.07 $\pm$ 42.93	134.22 $\pm$ 52.36	1.05 (0.10, 2.00)	Moderate
	2000 AVE Power	206.00 $\pm$ 44.51	142.78 $\pm$ 47.80	1.33 (0.34, 2.32)	Moderate
PSP	Total AVE Power	460.64 $\pm$ 66.08	323.52 $\pm$ 100.86	1.63 (0.60, 2.66)	Large
	Total AVE SPM	44.50 $\pm$ 3.95	46.74 $\pm$ 7.97	-0.37 (-1.27, 0.53)	Small
	Peak Power	516.00 $\pm$ 81.94	351.06 $\pm$ 105.73	1.73 (0.68, 2.78)	Large
	Peak Stroke SPM	46.89 $\pm$ 4.74	48.31 $\pm$ 7.84	-0.22 (-1.11, 0.67)	Trivial
CMJ	Jump Height	0.35 $\pm$ 0.06	0.31 $\pm$ 0.08	0.56 (-0.34, 1.47)	Small
	Time to Take-Off	0.95 $\pm$ 0.15	0.96 $\pm$ 0.24	-0.07 (-0.96, 0.82)	Trivial
	RSI mod	0.38 $\pm$ 0.08	0.35 $\pm$ 0.15	0.23 (-0.66, 1.12)	Trivial
	Net Impulse	184.60 $\pm$ 25.83	146.63 $\pm$ 39.80	1.15 (0.19, 2.11)	Moderate

Bold indicates a significant effect size $p < 0.05$

IMTP: isometric mid-thigh pull; IHT: isometric hip thrust; PSP: peak stroke power test; CMJ: countermovement jump; JH: jump height; RSI mod: reactive strength index modified; AVE: Average; Peak Force/Mass: peak force divided by body mass; SD: standard deviation; LL: lower limit; UL: upper limit.

Following the evaluation of all the participants percentage predicted adult height (%PAH), their maturation status was banded and nine were calculated to be circa PHV (mid-late pubertal) and 14 were banded as post PHV (post pubertal). Between-group differences are presented in Table 3. Significant between-group differences existed for: IMTP peak force ($g = 1.81$), IMTP force at 300 ms ($g = 1.04$), IMTP peak force / mass ($g = 1.57$), IHT force at 300 ms ($g = 1.10$), 2 km ergometer total time ($g = -1.30$), 2 km ergometer average power ($g = 1.12$), average power during all 500 m splits of the 2 km ergometer test ($g = 0.94$ -1.33), PSP total average power ($g = 1.63$), PSP peak power ($g = 1.73$), and

CMJ net impulse ($g = 1.15$). Furthermore, an overview of all participants TSA data are displayed in Figure 1.

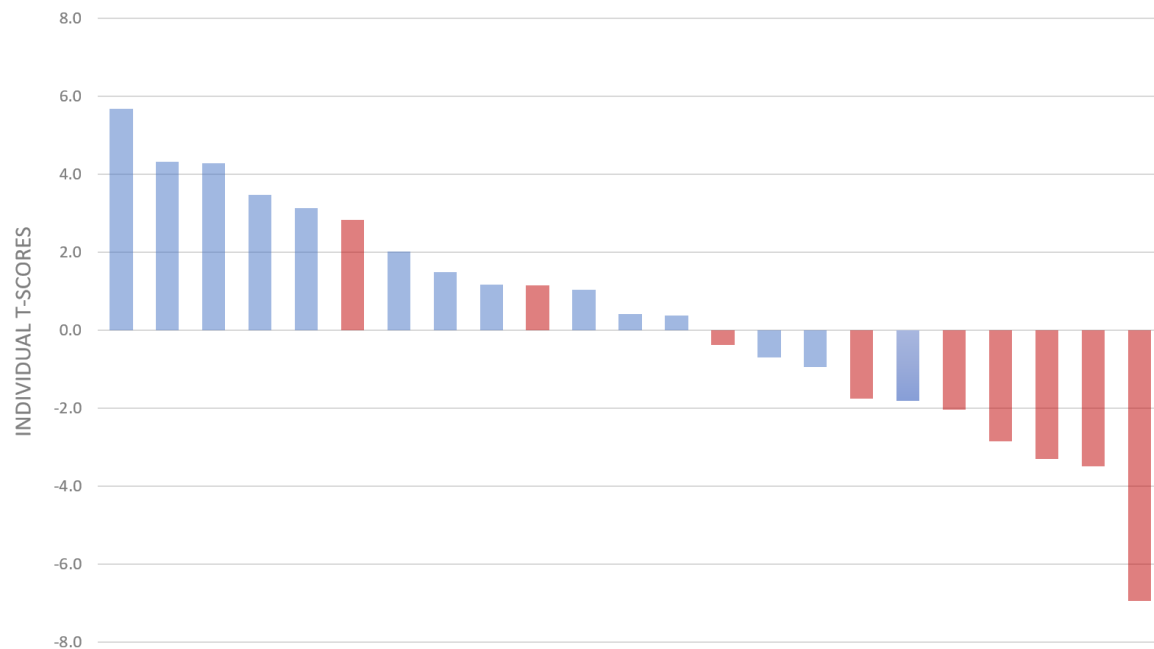


Figure 1. Total score of athleticism data for the group ($n = 23$). *Note:* Blue bars indicate post pubertal rowers and red bars indicate circa (mid-late) pubertal rowers.

DISCUSSION

The aim of the present study was to examine the associations between maximal and rapid force production measures with rowing ergometer performance, in youth male rowers. Results show that net impulse from the CMJ had the largest relationship with rowing performance from all physical test measures. Additionally, IMTP peak force and force at 300 ms showed large to very large correlations with rowing ergometer performance. When assessing between-group differences for maturation status, significant differences were evident for many physical and rowing-specific qualities, outlining the sensitivity of particular tests and metrics to detect differences in performance with both age and maturation status.

Firstly, it is important to consider the reliability of performance metrics when aiming to inform coaching practice (53). In the present study, physical performance metrics ranged from poor to good reliability as highlighted in Table 1. Of particular note, force at 100 and 200 ms, for both the IMTP and IHT displayed poor reliability (CV: 13.34%, 13.27% and 25.42%, 17.24%, respectively). Additionally, IHT force at 300 ms also showed borderline acceptable CV of 10.72%, indicating notable variability in test scores for most of the rapid force production metrics in the isometric protocols. Whilst not what practitioners would necessarily want to see reported, these data are synonymous with results from recent research which has also reported similar metrics in adult and youth golfers (7,41). As such, it is suggested that practitioners are initially mindful of the utility of these rapid force production metrics, but also consider appropriate levels of test familiarisation in an attempt to make these variables as usable as possible.

The findings of the present study showed very large correlations between CMJ net impulse and a range of rowing performance measures (Table 2). Intuitively, this is expected even though previous studies haven't explicitly reported impulse as a metric from the CMJ. Previous rowing-related research has reported that CMJ height is significantly correlated with various rowing ergometer performance metrics (25,33,39). Given previous research has shown that the mechanistic determinant of jump height is impulse (42), it stands to reason that this metric would also exhibit strong associations. Importantly as well, net impulse was quantified via inverse dynamics, whereby velocity at take-off was determined by the jump height scores multiplied with the athlete's body mass. Thus, with both jump height and body mass being two very accessible measures for practitioners, we would suggest that there are minimal reasons for practitioners to not quantify this metric, even when they do not have force platforms.

When considering the IMTP, large to very large associations were present with rowing ergometer performance; predominantly the PSP test. These findings partially align with those of Ledergerber et al. (31) who reported that both IMTP peak force and IMTP RFD over 300 ms shared very large

correlations with 2 km rowing ergometer performance, also in junior rowers ($r = -0.908$, $p < 0.01$, and $r = -0.812$, $p < 0.01$, respectively). Initially, both IMTP peak force and IMTP force at 300 ms appeared to both have very similar utility. The large associations with force at 300 ms may be explained by the fact that this timeframe is likely to represent a useful proxy measure for the time required for rowers to produce peak force when rowing (21). However, the similarity in correlations with peak force is actually not surprising as the determinants of force production for these two metrics are essentially very similar (i.e., neuromuscular factors), as outlined in a recent review on the dynamic strength index (6). Further to this, although relationships between peak force or force at 300 ms with 2 km rowing performance were comparable, peak force associations were stronger with the PSP protocol. Therefore, we suggest that peak force is not only more reliable, but also probably serves as a better proxy than rapid force production measures, in youth rowers. Whilst somewhat speculative, this may be due to the fact that the present sample was a youth population, where maximal force production is likely to be a more defining factor, owing to the varying rate of physical development associated with maturation (32).

The present study also found some large to very large correlations between specific IHT metrics and some rowing ergometer performance measures. These data indicate the importance of the hip and back extensor muscles, but interestingly, only for maximal effort rowing – as defined by the PSP protocol, which is in agreement with recent research (31). However, the poor reliability for force at 200 and 300 ms in the IHT means that practitioners should again consider these relationships with some degree of caution, reiterating the importance of test familiarisation. Thus, it is suggested that the IHT protocol is likely to be of less value than the IMTP and CMJ assessments, when assessing physical profiles for rowing populations.

In the present study, the participant group was split into circa (mid-late) and post pubescent sub-groups based on their estimated maturation status. Significant between group differences were most commonly evident in the rowing specific assessments. With PSP rowing ergometer performance

measures showing significant large between group differences, PSP total average power ($g = 1.63$), PSP peak power ($g = 1.73$). Additionally, all 2 km rowing ergometer performance measures also showed significant moderate between group differences: total time ($g = -1.30$), average power ($g = 1.12$), first 500 m power ($g = 0.94$), second 500 m power ($g = 0.95$), third 500 m power ($g = 1.05$) and the fourth 500 m power ($g = 1.33$). This finding supports previous research which suggests advantageous metabolic and physiological changes occur during maturation, leading to improvements in aerobic and anaerobic fitness, potentially as a result of increases in heart size, blood volume, haemoglobin content and anaerobic enzyme activity (32,50).

The largest significant between-group difference in the isometric test measures was IMTP peak force ($g = 1.81$), whilst net impulse ($g = 1.15$) was the only significant between-group difference for the CMJ. These two physical assessment metrics were also reliable and held the strongest, most consistent relationships with rowing ergometer performance, as previously stated in the present study. Therefore, being able to discriminate between maturation groups only further supports the utility of these metrics over others when comparing, assessing and improving junior male rowers' performance. Furthermore, the present study's findings also align with the consensus within the literature that both maximal and ballistic force production improve during adolescence as a result of maturation (50). Hence, the between group differences reported were not surprising as training experience and maturation status influences the extent to which physiological, neurological and morphological adaptations have occurred (12,37).

There are specific limitations within this study that should be considered when interpreting the findings. Firstly, only junior male rowers were included in this study, which reduces the generalisability of the findings to wider populations. Secondly, due to the novel use of the Force Hooks 2 (Ascend Labs., AUS), a 20 N threshold was utilised for the force-time analysis. Whereas, recommendations which use a similar protocol with force plates have suggested other thresholds which may have improved the reliability of early force-time data (13). Thirdly, it is possible that the use of a peak power

ergometer test resulted in some detrimental effects on technique. Specifically, it is not uncommon to for rowers to lose the use of a leg-driven rowing stroke when attempting to maximize power output, which in turn, results in the rowing stroke becoming more spinal and shoulder extension-driven. Unfortunately, this was not monitored in the present study but future investigations should be mindful of this and ensure technical execution is reinforced. Finally, the present study chose to assess maximal force production capabilities via two isometric protocols. It is acknowledged, that other methods of assessing maximal force production also exist (e.g., 1-3RM leg press), which may also hold utility for practitioners owing to them being dynamic in nature, and arguably, may be just as good as the IMTP as a physical proxy measure.

PRACTICAL APPLICATIONS

Despite the present study being associative by design and focusing on cross-sectional data, we believe the findings can help promote important day-to-day changes in coaching practice for two reasons. Firstly, the present study has illustrated the importance of net impulse during the CMJ as a critical proxy measure to monitor. Not only was this metric reliable, but the present study illustrates this as a cheap and effective way to include this in the boathouse environment, making it accessible for all practitioners working with rowers, irrespective of their budgets. Second, the associations with IMTP data demonstrate that force production is 'slow in its rise' in rowing, indicating that slow stretch-shortening cycle exercises are likely the most relevant to include in programming from a maximal and ballistic force production perspective. Specifically, because rowers are required to go through large ranges of motion at the knee and hip joints, exercises which focus on similar ranges of motion (e.g., back squats and even jump squats) not only mimic the joint range experienced in rowing, but also help to align force production characteristics to the slow stretch-shortening cycle mechanics seen in the sport. Naturally, this reinforces support for using test measures such as the IMTP and CMJ specifically, when working with rowing populations.

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