CHARLES UNIVERSITY

Faculty of Physical Education and Sport

Anthropometrical, physiological, strength and other determinants of rowing performance - review of correlation-predictive analyses

DIPLOMA THESIS

Thesis supervisor: PhDr. Jan Busta PhD.

Thesis co-supervisor: prof. PhDr. Jiří Suchý PhD.

Author: Bc. Jaroslav Hellebrand

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Hereby I declare that I wrote my diploma thesis independently, and that I have stated all the information sources and literature I used. Neither this thesis nor any substantial part of it has been submitted for the acquisition of another or the same academic degree.

In Prague, ……………………………

Author´s signature

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Chtěl bych zde poděkovat především Vám, mami, tati, rodino, za hodnoty, které jste mi předávali a celoživotní podporu. Dále vedoucímu práce PhDr. Janu Bustovi PhD. za pomoc i volnost jež mi poskytl během relizace práce, stejně tak za intelektuální stimulaci, kterou mi interakce s ním přinesly nejen v souvislosti s realizací této práce. V neposlední řadě patří poděkování prof. PhDr .Jiřímu Suchému PhD., který mě na spoustu myšlenek v souvislosti s touto prací přivedl.

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Abstrakt

Název: Antropometerické, fyziologické, silové a další determinanty veslařského výkonu – review korelačně prediktivních analýz

Cíle: Na základě provedení systematické literární rešerše identifikovat nejsilnější prediktor(y) veslařského výkonu.

Metody: Tato práce využívá standardních metod pro relizaci přehledových prací: vyhledávání v databázích, extrakce a syntéza dat.

Výsledky: Z celkového počtu 534 studií bylo do výsledné review zařazeno 24 článků. Identifikovali jsme 11 prediktorů výkonu s vysokým korelačním koeficientem; Tělesná hmotnost (kg), Aktivní tělesná hmota (kg), VO2Max (L/min), Výkon na úrovni VO2Max (W), Výkon na úrovni 4mml LA (W), Tělesná výška (cm), Průměrný, Maximální a Minimální výkon v testu Wingate (W), Leg Press 1 Opakovací Maximum (kg) a test na 2000m na veslařském trenažeru.

Klíčová slova: veslování, analýza výkonu, korelace, predikce výkonu, review

Abstract

Title: Anthropometrical, physiological, strength and other determinants of rowing performance - review of correlation-predictive analyses

Objectives: To conduct a systematic literature review to search for a best single performance variable(s) (a measure of performance) that is(are) associated with rowing performance.

Methods: This thesis utilizes usual review methods in a form of database search, synthesis, and data extraction.

Results: After the initial screening of 534 articles the total of 24 articles was included in this thesis for review. We identified 11 performance variables with high coefficient of correlation; Body Mass (kg), Lean Mass (kg), VO2Max (L/min), Power at VO2Max (W), Power at 4mml (W), Body Height (cm), Wingate mean (W), Wingate maximal (W), Wingate minimal (W), Leg Press 1RM (kg), and 2000m rowing ergometer score.

Keywords: rowing, performance analysis, correlation, performance prediction, review

Contents

LIST OF ABBREVIATION

FISA – Fédération Internationale des Sociétés d'Aviron

EBR – Evidence Based Research

OG – Olympic Games

LWT – Lightweight category

HWT – Heavyweight category

LM – Lightweight men

LW – Lightweight women

1. EDITORIAL

In the world of elite sport, there is a broad area of parameters that are observed, evaluated, and measured. This goes for every modern professional sport not only for rowing on which this thesis has its focus on. Every sport, every discipline, every category, has its own robust performance predictors that explain, to a larger or smaller extent, the performance in a said sport. For example in road cycling, the watts per kilogram of body weight, also known as power to weight ratio is the golden performance predictor of competition results where higher w/kg usually prevails (Sitko et al. 2020; Westmattelmann et al. 2022). In running there is a clear consensus about the predictive strength of Cooper´s test and running velocity at ventilator/lactate breakpoints and velocity at VO2Max (Alvero-Cruz et al. 2020; Billat, Koralsztein 1996; Alvero-Cruz et al. 2019).

In rowing, the situation differs. There is a general agreement among coaches and scientists that rowers should be tall, muscular therefore strong, and lean coupled with exceptional aerobic and anaerobic capabilities. This is something we do not need a science for. Anyone can look at the winners at competitions and arrive to the same conclusion. But what we need the science for is to find out how much exactly is rowing a sport for all rather than sport for tall. What are the predictive measures of rowing performance? How much is performance in rowing based upon these specific measures of strength, endurance, and body dimensions? We can safely go with the flow here and say that strong, tall, and gifted in an endurance department is a good starting point but to be honest this is true in many sports and not just in individual sports. The same can be said for basketball, football, and volleyball and in the equivalent manner as for cross-country skiing and other sports. Even in cycling where power to weight index is a key to victory, there is a need for the "bigger guys" to protect them in the peloton and shield them from the wind, this is the task that sprinters and all-rounders fulfil for climbers during world tour competitions. We know of the body dimension differences there as reported in literature (Sánchez-Muñoz et al. 2022). Analogy: is cycling analogy; is there also in rowing the optimal body structure and physiological structure and does this structure differ for each seat in the crew?

To circle back to the topic at hand, there is need to identify exact performance predictors in rowing and subsequently their lower limit values that are required for achieving certain performance level. To put it simply, we need to know what tests to use when selecting rowers, what to measure and what to focus on. Not only for selection purposes but also and mainly for training purposes. The logic here should be a circle of A->B->C->A, where "A" is the performance/racing, “B” being the testing and “C” being the training. In theory we could enter this problematic cycle at any stage but that is only possible due to the already gathered knowledge, a bit of a chicken or an egg situation. The performance “A” is based on variables “B” therefore we need to train and improve those variables “C”.

It is unlikely that we are going to start from a scratch a rediscover America but at the same time it is necessary to beware of the bias that comes in current established knowledge. To offer an example, in rowing we (“we” means rowing coaches in this case) can argue for an hour whether the optimal oar length for specific athlete is 288 cm or 287 cm but what if it is 350 or 210 cm. When was the last time someone really stepped out of the box with their approach to problem solving a looked at it with entirely unique perspective? Are we really that certain, are we that far, so knowledgeable that we can be sure?

You may disagree with my ABCA circle, and I even dare you to, we can all be improved by healthy disagreement. I am going to offer one other look the whole testing problem. Again, using my favourite “dry” sport as an example; in cycling, unlike in rowing they allowed the use of power meters in competitions. This has brought enormous amount of data, but not just a data but the competition data, the big data. It allowed for quantifying the cycling performance in the most exact viable way. The question is whether this did not result in more problems than benefits due to everyone focusing on maintaining their critical power during the race rather than pure racing by feel. It can be argued that it sterilized the racing, but now we know the exact power measures in a cycling race whereas in rowing this is still not possible due to the FISA rules limiting the use of such devices in competitions. A closer look at the actual rowing performance in competition, rather than repeated laboratory testing and transfer of rowing into weightlifting exercises could bring the desired information about the requirements of the sport and perhaps even change the way we train and test.

2. STUDY INTRODUCTION AND RESEARCH PROBLEM

A useful measure of rowing performance must have acceptable validity, as well as reliability (Smith, Hopkins 2012). For the purpose of this study these measures are expressed in a form of an individual anthropometric, somatic, and physiological or another variable. It can be a specific performance test used in rowing environment in laboratories or during a field testing. If this parameter correlates with rowing performance, it is simultaneously called a predictor. We aim to conduct a systematic literature review to search for a best single performance variable (a measure of performance) that is associated with rowing performance. This is necessary since rowing environment still lacks consensus regarding the optimal tools for athlete selection as is illustrated by various selection criteria implemented in rowing by governing bodies and institutions. We strive to provide evidence-based claims, which can be further used to help athletes, coaches, and scientist to decide on better criteria when selecting athletes to supported groups (national teams, performance centres, etc…). Subsequently, we hope this thesis will identify gaps and limits in knowledge regarding this problematic.

Systematic reviews, which developed in the social sciences in the 1970s, began to gain rapid momentum during the 1990s in response to concerns by policymakers and clinicians about the scientific validity of the prevailing paradigm of traditional narrative reviews written by authoritative experts (Moher et al. 2015). What distinguished systematic reviews was the use of formal explicit methods, in other words pre-specification, of what exactly was the question to be answered, how evidence was searched for and assessed, and how it was synthesized in order to reach the conclusion (Moher et al. 2015). Systematic review methods are increasingly applied to the more traditional types of review, including literature reviews, hence the proliferation of terms like 'systematic literature review' and many more (Mellor Portsmouth 2021), a scoping review in case of this thesis. Over the last two to three decades, meta-research has shown a high number of redundant and unnecessary studies being published. The best way to avoid redundant research would be to identify or prepare a systematic review of earlier similar studies and use this systematic review to justify and inform the design of a new study, and to place new results in context. This process is called evidence-based research (EBR) (Pieper, Lund 2023). In other words, systematic reviews are necessary to stop discovering what is already discovered and sort out current knowledge.

3. INTRODUCTION TO ROWING

Rowing is an strength/power – endurance type of sport, and morphology and mass are undoubtedly performance related factors (Busta et al. 2023) with events described as supra - maximal, performed with power outputs above the associated with the maximal rate of oxygen uptake (Secher 1993). Strength and power seems to be one of the key aspects of rowing performance since rower who achieve greater net power were also able to achieve higher boat speeds therefore faster times in competitions (Lawton et al. 2013). From an endurance standpoint, it was found that aerobic contribution is around 84% - 87% (Russell at al. 1998; De Campos Mello et al. 2009), but there are others speculating on the contribution of aerobic and anaerobic energy pathways. This is going to be important dispute to settle going forward because of the planned changes for 2028 Los Angeles Olympiad, since this energy profile is likely going to change (Astridge et al. 2023; Volianitis et al. 2022; Moran 2021).

Olympic rowing in its current form stretches its competition distance over 2000m long regatta course. For the athletes competing in up to 22 boat classes although not all of them are featured on the Olympic program since it is undergoing a constant change. This means athletes spend from 5 minutes 30 seconds to 7 minutes 30 seconds in the race at maximal intensity (FISA 2019; Grasgruber, Cacek 2008).

As it was mentioned before there are up to 22 boat classes in international rowing regattas, consisting of heavyweight or lightweight rowers, singles or crewed boats of multiple athletes, coxed boats with a coxswain in a stern or a bow or without a coxswain altogether (Smith, Hopkins 2012). Anglo-Saxon rowing world focuses mainly on sweep rowing, which they call just rowing. It comprises of a pair, primarily coxless (2-), but sometimes coxxed (2+), a four in a coxless variant (4-) or a coxxed variant (4+) and the eight (+8) which always has the cox present in the boat. Athlete in sweep rowing operates one large oar on single side of the boat however this is different in sculling where rowers control one smaller oar in each hand. Sculling disciplines both start and end with smaller boats than sweep; single scull (1x), double scull (2x) and quadruple scull (4x). Most of the boat classes are also raced by lightweight rowers with an abbreviation of LM for men and LW for women, e.g. (LW2x) (FISA 2019).

Lightweight rowing was introduced to the program of the Olympiad in 1996 Atlanta games, but these days nearly 30 years later it is being slowly pushed out of the Olympic program again. Lightweight rowers are by rules limited by maximal individual and average crew weight. For male rowers, this limitation is that no single rower can exceed 72.5 kg, with the crew average not exceeding 70 kg. This rule is further downscaled for female to 59 kg maximal weight and 57 kg of a crew average (FISA 2019). Such regulation applies in close time proximity to the race unlike in most combat sports, rowers must make the weight 120 – 60 minutes prior the start.

A closer look on body anthropometry, endurance and strength capabilities of rowers is warranted to better understand the context of this thesis and its implications. As it was previously mentioned there are two different weight categories in rowing lightweight (lw/lwt) and heavyweight (hw/hwt) also sometimes referred to as open weight or open class category. Both categories are very distinct from one another since the weight limitation rooted in rules in the end influences way more than just the weight itself. Elite rowers in heavy weight category can be characterized by large body dimensions in all measured aspects, as reported by Busta et al. (2023) (Table 1), similar findings are reported by other authors; the overall findings suggest that the fastest rowers tend to be the largest and strongest rowers (Barrett, Manning 2004). Based on the reports from published articles it is uncommon to find world class heavy weight male rowers with height under 185 cm (Akça 2014; Busta et al. 2023).

Hand in hand with body dimensions however scales requirements for strength and power. To illustrate these requirements, we present lower limit recommended indexed values of body weight for powerlifting exercises as reported by McNeely et al. (2005) (Figure 1, Figure 2). I.e., body weight multiplied by the index value from the table is the desired performance at lower performance limit.

	High school (*n* = 154)	**U23** (*n* = 91)	**Club** (*n* = 103)	**National** (*n* = 40)	**Olympic** (*n* = 26)
Squat	1.0	1.3	1.4	1.7	1.9
Deadlift	1.0	1.3	1.4	1.7	1.9
Bench Pull	0.7	0.9	1.05	1.2	1.3

Figure 1 - Strength to Body Weight Factors for Men, McNeely et al. (2005)

	High school (*n* = 166)	**U23** (*n* = 97)	**Club** (*n* = 146)	**National** (*n* = 48)	**Olympic** (*n* = 31)
Squat	1.0	1.0	1.25	1.4	1.6
Deadlift	0.8	1.0	1.25	1.4	1.6
Bench Pull	0.6	0.8	0.95	1.1	1.2

Figure 2 - Strength to Body Weight Factors for Women, McNeely et al. (2005)

The measurement of anaerobic power i.e., anaerobic energy system fitness is most often measured by using a Wingate test. From Wingate test we can observe several parameters with the most common ones being Mean Power, Maximal Power, Minimal Power, and so-called fatigue index which indicates the decline of power during the test. Wingate has various form but usually it is a 30 second all out test. Frequently we can see a name *modified Wingate* which indicates change in the duration of the test or change in the test rig used to measure the performance, since the *classical Wingate* is done on a cycling ergometer. Here we present peak and average performance from 30 seconds modified rowing ergometer Wingate test protocol as reported by McNeely et al. (2005)

Category	Peak power (watts)	Average power (watts)
Heavyweight men (*n* = 41)	900–1100	725–875
Lightweight men (*n* = 32)	650–800	510–720
Heavyweight women (*n* = 54)	550–700	380–475
Lightweight women (*n* = 27)	400–500	350–425

Figure 3 - Peak and Average in a Wingate, McNeely et al. (2005)

Based on previous reports (Grasgruber, Cacek 2008; Droghetti et. al 1991; Hellebrand 2020) we also know that the value of VO2Max is high in rowers. It is reported to be in a range of 70 – 80 (ml/kg/min) in male and 50+ (ml/kg) in female. In absolute numbers this means 7 (l/min) and 4,5 (l/min) VO2Max values. The data on VO2Max values however vary across academic articles and studies, Sousa et al. (2014) reports relative VO2Max value around 66 (ml/kg/min) in heavy weight internationally competing men. Other recent studies that have looked at VO2Max in relation to rowing performance report maximal values at about 5,6 (l/min) in national and international heavyweight men (Bourdin et al. 2004; Nevill et al. 2011) which in relative values means around 68 (ml/kg/min) with a body weight of 88 kg. Cacek and Grasgruber (2008) also stress the importance of absolute value of VO2Max, rather than relative expression. This has to do with exponential drag of the water on the boat with increasing propulsive power expenditure. A rower's speed, therefore, should be proportional to the cube root (0.33) of power expended (Nevill et al. 2011).

Variable	Male rowers ($n = 46$)					Female rowers ($n = 22$)				
	Heavy weight ($n = 31$)	Light weight ($n = 15$)	Difference			Heavy weight ($n = 16$)	Light weight ($n = 6$)	Difference		
			p	*d*	%			*P*	*d*	%
Age (years)	25.6 ± 5.5	28.8 ± 6	0.04	0.56	11.1	23.6 ± 3	22.5 ± 1.4	0.19	0.42	4.9
Sport age (years)	11.3 ± 5.5	13.1 ± 6.4	0.16	0.31	13.7	9.9 ± 4.0	11.5 ± 2.0	0.19	0.43	13.9
Body mass (kg)	91 ± 8.8	72.3 ± 1.2	0.00	2.56	25.9	76.4 ± 5.5	59 ± 3.1	0.00	3.47	29.5
Height (cm)	189.9 ± 6.4	181.1 ± 4.3	0.00	1.51	4.9	178 ± 4.6	170.4 ± 3.8	0.00	1.72	4.5
Body mass index (kg/m^2)	25 ± 2	22.1 ± 1.1	0.00	1.77	14.0	24.1 ± 1.7	19.9 ± 0.4	0.00	2.85	21.1
Sitting height (cm)	90.4 ± 3.6	86.6 ± 2.6	0.00	1.17	4.4	85.2 ± 3.1	82.1 ± 2.5	0.01	1.06	3.8
Arm span (cm)	192.6 ± 6.5	182.9 ± 5.8	0.00	1.53	5.3	178.8 ± 5.2	172.1 ± 2.7	0.00	1.44	3.9
Sitting height/body height (%)	47.6 ± 1.3	47.8 ± 1.3	0.3	0.14	0.4	47.9 ± 1.3	48.2 ± 0.9	0.3	0.25	0.6
Arm span/body height (%)	101.4 ± 2.5	101.0 ± 2.1	0.28	0.18	0.4	100.4 ± 2.3	102.0 ± 3.1	0.31	0.63	1.6
Shoulder breadth (cm)	46.7 ± 2.8	44.4 ± 2.6	0.00	0.86	5.2	43 ± 1.9	41.1 ± 2.2	0.03	0.93	4.6
Humerus breadth (cm)	7.6 ± 0.4	7.2 ± 0.5	0.00	1.09	5.6	6.4 ± 0.8	6.3 ± 0.3	0.36	0.17	1.6
Femur breadth (cm)	10.9 ± 0.7	10.1 ± 0.5	0.00	1.21	7.9	10.1 ± 0.7	9.3 ± 0.2	0.00	1.47	8.6
Forearm girth (cm)	30.1 ± 1.4	27.9 ± 1.3	0.00	1.62	7.9	26.3 ± 1	24.4 ± 0.8	0.00	2.15	7.8
Flexed arm girth (cm)	36.6 ± 2.1	32.6 ± 2.1	0.00	1.93	12.3	31.6 ± 1.5	27.7 ± 1.1	0.00	2.79	14.1
Chest girth (cm)	98.2 ± 5	91.7 ± 2.7	0.00	1.46	7.1	81.4 ± 6.4	75.5 ± 3.7	0.16	1.09	7.8
Thigh girth (cm)	57.8 ± 3.9	51.5 ± 2.3	0.00	1.79	12.2	57.5 ± 3.5	52.1 ± 1.1	0.00	1.75	10.4
Calf girth (cm)	39 ± 2.1	35.3 ± 1.5	0.00	1.9	10.5	37.8 ± 1.7	33.8 ± 0.9	0.00	2.55	11.8
Sum of 5 skinfolds (mm)	35.9 ± 7	26 ± 3.8	0.00	1.61	38.1	50.7 ± 12.4	36.1 ± 12.1	0.01	1.19	40.4
Body fat (%)	12.9 ± 4.1	8.3 ± 3.2	0.00	1.19	55.4	23 ± 3.5	15 ± 3.1	0.00	2.37	53.3
Endomorphy	2.2 ± 0.5	1.5 ± 0.7	0.00	1.15	46.7	3.1 ± 0.8	2.0 ± 0.8	0.00	1.38	55
Mezoporphy	5.6 ± 1.0	4.6 ± 1.2	0.02	0.90	21.7	4.4 ± 0.9	3.7 ± 0.5	0.00	0.96	18.9
Ectomorphy	2.3 ± 0.8	3.2 ± 0.7	0.00	1.19	28.1	2.1 ± 0.7	3.4 ± 0.6	0.00	1.99	38.2
Hand-grip right hand (kgf)	59 ± 8.9	51.6 ± 6.8	0.02	0.89	14.3	40.8 ± 6.7	33.1 ± 5.3	0.00	1.22	23.3
Hand-grip right hand relativized (kgf.kg^{-1})	0.7 ± 0.1	0.7 ± 0.1	0.04	0.57	0	0.5 ± 0.1	0.6 ± 0.1	0.2	0.41	16.7
Hand-grip left hand (kgf)	58.2 ± 8.3	50.1 ± 6.6	0.00	1.04	16.2	40.5 ± 7.6	32.2 ± 4.4	0.00	1.19	25.8
Hand-grip left hand relativized (kgf.kg^{-1})	0.6 ± 0.1	0.7 ± 0.1	0.06	0.49	14.3	0.5 ± 0.1	0.6 ± 0.1	0.3	0.25	16.7
TBW (%)	62.3 ± 3	65.4 ± 2.8	0.00	1.06	4.7	56.7 ± 2.6	59.9 ± 2.5	0.00	1.26	5.3
ECW/TBW (%)	33.2 ± 1.2	35 ± 1.2	0.00	1.48	5.1	35 ± 2.4	36.8 ± 0.9	0.00	0.85	4.9

Table 1 - Anthropometry of elite rowers Busta et al. (2023)

3.1. CORRELATION

Correlation is a the method of analysis to use when studying possible association between two continuous variables (Altman 1999). It is important to stress that correlation is different from causal dependence. If two variables are correlated, it does not necessarily mean that one influences the other. In a more detailed statistical analysis, we can ask whether the correlation coefficient is large enough that there is indeed a relationship between the observed variables. It is simple both to calculate and to interpret; the term correlation is sometimes used loosely in verbal communication. Among scientific colleagues, the term correlation is used to refer to an association, connection, or any form of relationship, link or correspondence (Mukaka 2012). Pearson correlation coefficient is a mean of descriptive statistics, meaning that it summarizes the characteristics of a dataset. Specifically, it describes the strength and direction of the linear relationship between two quantitative variables (Turney 2022). Correlation between two variables indicates that changes in one variable are associated with changes in the other variable. However, correlation does not mean that the changes in one variable actually cause the changes in the other variable (Frost 2018).

Mukaka (2012) states that for a correlation between variables x and y, the formula for calculating the sample Pearson's correlation coefficient in a following form.

$$r = \frac{\sum_{i=1}^{n} (x_i - x)(y_i - y)}{\sqrt{\left[\sum_{i=1}^{n} (x_i - \bar{x})^2\right]\left[\sum_{i=1}^{n} (y_i - \bar{y})^2\right]}}$$

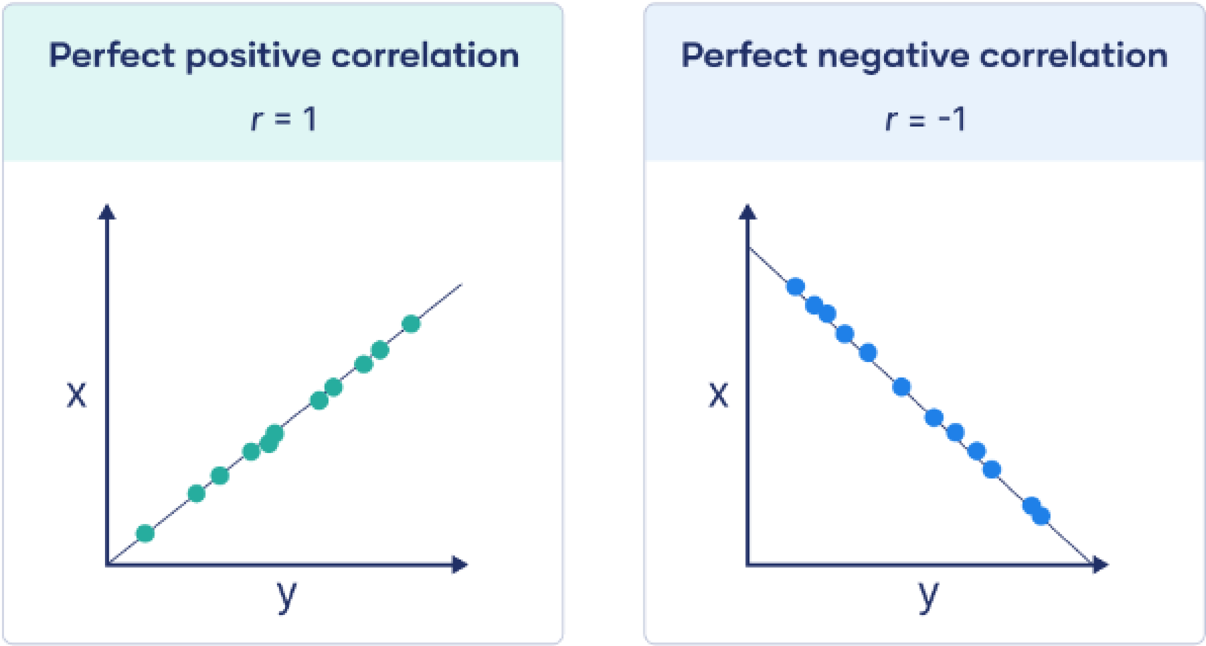
For a population parameter, the Pearson's product moment correlation coefficient is represented as ϱ, and for a sample statistic, as r, the r parameter is what we focus on in this paper.

The Pearson correlation coefficient takes values from -1 through 0 to +1, where the extreme (-1 and +1) values indicate absolute/perfect correlation and 0 indicates no correlation. If both values trend in the same direction, i.e., both increase or decrease, the correlation is positive. However, if one of the values is decreasing and the other is increasing, we get a negative correlation. This is the case for most parameters associated with rowing performance when one of the variables is the time achieved over a certain distance. One example of a negative but very strong correlation is the VO2Max level (l/min) where this phenomenon is normally observed. A negative correlation sounds suspiciously like no relationship. However, the scatterplots for the negative correlations display the real relationship. For negative correlation coefficients, high values of one variable are associated with low values of another variable. For example, there is a negative correlation coefficient for school absences and grades. As the number of absences increases, the grades decrease (Frost 2018). This is important to understand since high negative correlation (i.e., r=-.891) is undeniably a stronger predictor than weak positive correlation (i.e., r=.554).

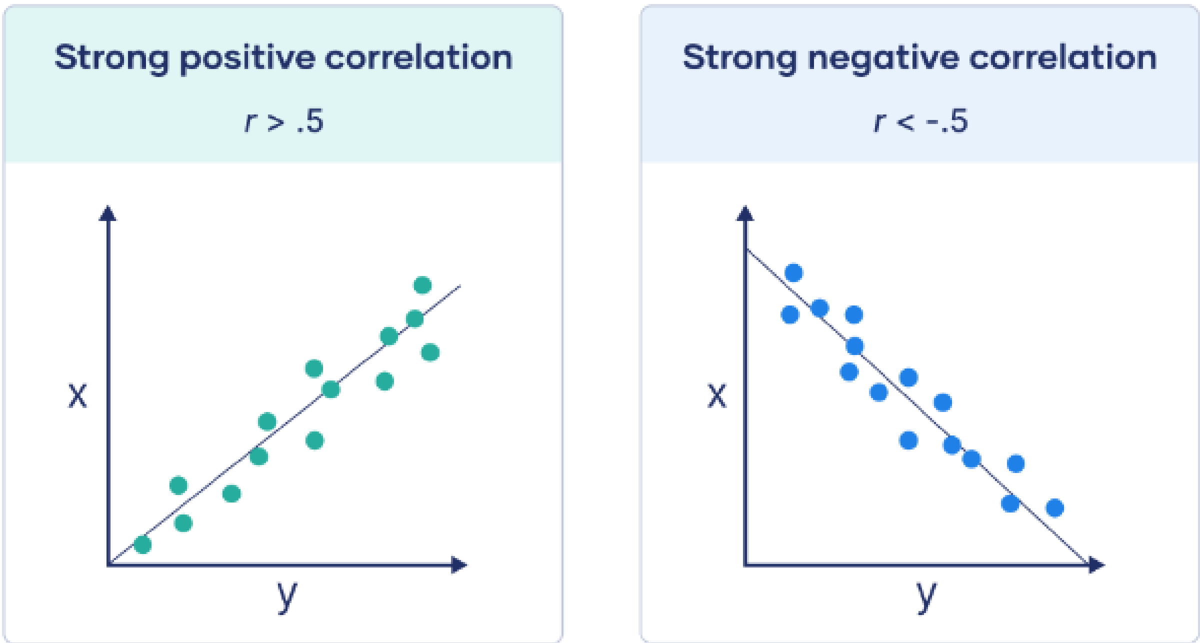
We adopted Rule of Thumb for Interpreting the Size of a Correlation Coefficient (Clarke et al. 1978; Mukaka 2012; Altman 1999) in a following form.

Size of Correlation	**Interpretation**
• .90 to 1.00 (−.90 to −1.00)	Very high positive (negative) correlation
• .70 to .90 (−.70 to −.90)	High positive (negative) correlation
• .50 to .70 (−.50 to −.70)	Moderate positive (negative) correlation
• .30 to .50 (−.30 to −.50)	Low positive (negative) correlation
• .00 to .30 (.00 to −.30)	negligible correlation

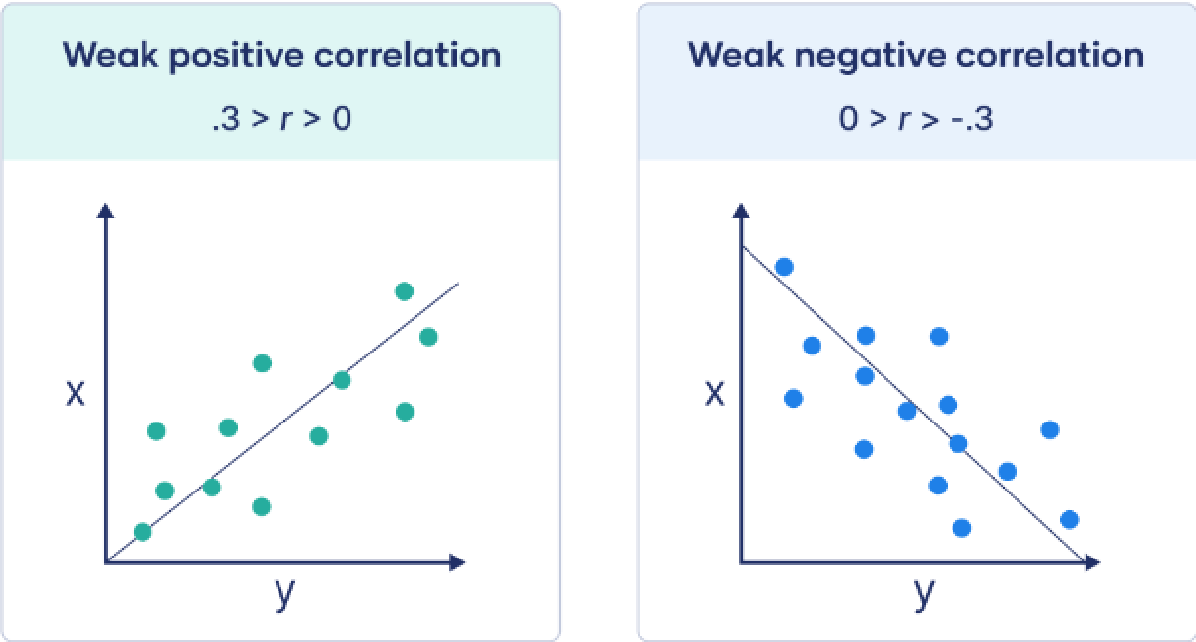
Although Tourney´s (Turney 2022) graphic example of scatterplot distribution for different strength of correlation differ in terminology, they are sufficient to illustrate different strengths of correlations. Correlation of (r=1/r=-1) is in sport science practise exceedingly rare, practically non-existent. It shows perfect linear dependence of two variables (Picture 1). (Picture 2) illustrates a strong correlation of (r>.5/ r<-.5).



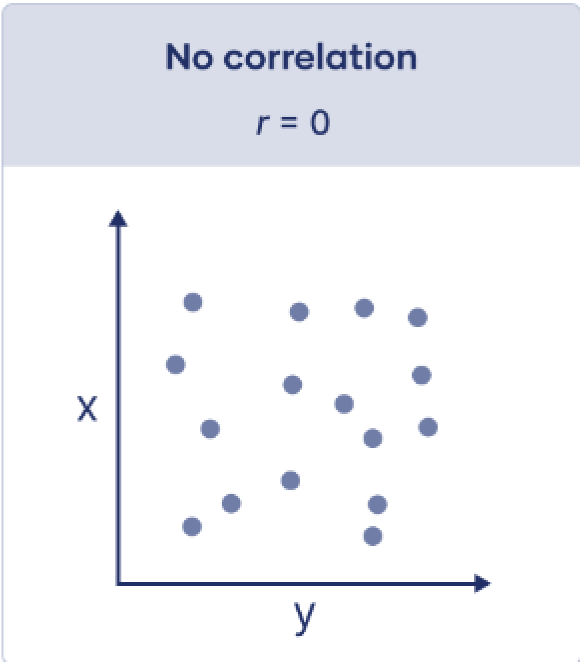
Picture 1 - Perfect Correlation, Turney (2022)



Picture 2 - Strong Correlation, Turney (2022)

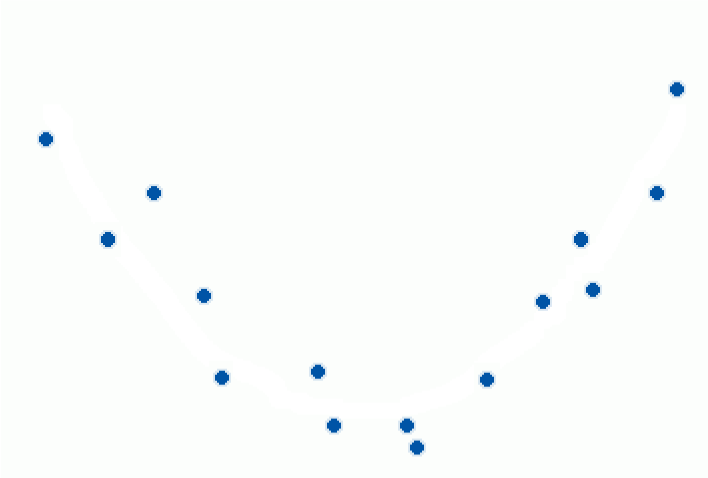


Picture 3 - Weak Correlation, Turney (2022)



Picture 4 - No Correlation, Turney (2022)

There is but one more point that is necessary to understand in connection with Pearson´s correlation coefficient, being that it only reveals linear relationship. To phrase this in other words, the Pearson´s correlation coefficient may miss a relationship or give a false impression of its strength if the relationship between two variables is curved or otherwise non-linear rather than linear. That is also one of the reasons why it is important for researchers using correlation to graph the data as suggested by Frost (2018). We can safely say that there is no relationship whatsoever in the dataset in picture 4, however the same cannot be said for the dataset in picture 5 even though they both correlate at r value of (r=.0). There is a clear trend in the dataset presented in Picture 5, it just is not linear and a Pearson´s correlation will not be able to reveal this.



Picture 5 - Non-linear relationship, Frost (2018)

3.2. PERFORMANCE TESTING

A useful measure of rowing performance must have acceptable validity, as well as reliability (Smith, Hopkins 2012) we would also argue that a test must be sufficiently sensitive. Diagnosis of performance is often conducted by means of testing, especially in cases where we aim to determine the level of movement abilities. A test is considered a standardized test when it meets the criteria for validity and reliability. Sometimes any examination is inaccurately referred to as a test (Busta et al. 2021). There are three factors that contribute to a satisfactory performance test.

3.2.1. VALIDITY

A valid protocol is one that resembles the performance that is being simulated as closely as possible (Currell, Jeukendrup 2008; Hohmann et al. 2010).

Here, we are interested in the concurrent validity which means that the performance protocol is correlated with a criterion measure (Currell, Jeukendrup 2008). In our case these are the individual variables of strength, endurance, anthropometry correlated to a specific rowing performance (criterion measure).

Despite the wide and common use of Concept 2 rowing ergometers there are to this day still relatively limited data on its validity and accuracy (Volianitis et al. 2022). The method of generating resistance via air dampening implies that the target mechanical output is critically influenced by the rower´s effort and associated with very high variability even in elite rowers (4 - 5%) (Treff et al. 2018). However, variability arising from environmental and other factors probably adds to the rower's inherent physiological variability in performance from race to race (Smith, Hopkins 2011). The current ergometry provides acceptable level of validity for rowing testing and allows the transfer of rowing into controlled conditions.

3.2.2. RELIABILITY

Reliable protocol provides a similar result from day to day when no intervention is used (Atkinson, Nevill 1998). It is an important measure since it gives an indication of the biological and technical variability of the protocol (Bagger et al. 2003). It is also possible to use correlation to asses' reliability via retesting and correlating the repeated results. Often used is a measure of Pearson´s product moment correlation (r) where a high significant correlation may lead to the conclusion that a protocol or a test is reliable (Currell, Jeukendrup 2008). Measures of performance derived from a rowing ergometer can and do have standard error of measurement less than 1% in reliability studies (Smith, Hopkins 2012).

3.2.3. SENSITIVITY

Test or protocol is sensitive when able to detect small, but important, changes in performance. It is important that even very marginal differences can be detected especially if those differences would be sufficient to cause a change in the competition results. This means that devices for measuring rowing speeds and/or power must be very precise. As the distance (more specifically time to completion) of the event increases, so too does the variation in performance (Currell, Jeukendrup 2008). The race-to-race variability in finish times for elite rowers in world championships and Olympic competitions is ∼1% (Smith, Hopkins 2011).

4. METHODS

4.1. OUTLINE

This thesis is a literature review with elements of systematic scoping review scientific approach. We would like to shed some light on specific measures of rowing performance; being specific physiological tests and parameters, strength tests, anthropometric variables and other exercises that are correlated to rowing performance in current literature. We aim to search scientific databases for studies that present valid and reliable predictors of rowing performance. This thesis is specifically interested in correlation coefficient of those predictors with rowing performance. In a way, it can be argued that we are searching for valid predictors of rowing performance. The snowball method will be subsequently used to search for additional studies that meet the inclusion criteria specified bellow. As previously conducted by (Lawton et al. 2013) the conclusion of this thesis are based upon peer – reviewed journal publications or conference proceedings.

The results of our search will be reported in the form of overview tables of specific predictors. Subsequently, if matching predictors emerge from the search, we aim to create additional overview table for it. Within limits, this thesis follows the PRISMA guidelines.

4.2. TYPE OF STUDY

For our purpose we define a scoping reviews as a report on the types of evidence that address and inform practice in the field and the way the research has been conducted (Munn et al. 2018) with the objective to identify and map the available evidence. Note that we will not focus on the methodology of the articles unless it is necessary within the purpose of this study. What interests us the most are the results; hence an argument can be made that this thesis is a sort of methodological hybrid between systematic scoping review and literature review.

4.3. AIM OF STUDY

We aim to conduct a systematic literature review to search for a best single performance variable (a measure of performance) that is associated with rowing performance since rowing environment still lacks consensus regarding the optimal tools for athlete selection as is illustrated by various selection criteria implemented in rowing by various institutions. The strive is to provide evidence-based claims, which can be furthered to help athletes, coaches, and scientist to decide for better criteria when selecting athletes to supported groups (national teams, performance centres, etc…). Subsequently, we hope this thesis will identify gaps and limits in knowledge regarding this problematic.

4.4. PARTICULAR OBJECTIVES

1. Database search to identify relevant articles.
2. Article screening phase 1– Title, Abstract
3. Article screening phase 2– Full text
4. Reference list screening (Snowball method)
5. Preparation of the summary tables
6. Reporting the results

4.5. SEARCH STRATEGY

Databases of scientific research; Scopus and Web of Sciences were searched for articles. Terms: rowing, performance, prediction were used in different variations to best identify relevant papers. Search was limited to Title, Abstract and Key Words, limited to relevant fields of research and limited only to studies published after year 2000.

4.6. PRISMA DIAGRAM

The Prisma diagram (Diagram 1) is used to report on each step of the review as recommended by PRISMA guidelines (Page et al. 2021).

The total of 534 studies was acquired from databases Scopus and Web of Science. Various combinations of Terms: rowing, performance, prediction were used to best suit the search engine of the databases. After removing duplicate papers, we were left with 355 studies that met the primary search criteria. Of those 355 studies 298 were excluded due to the topic mismatch apparent from the title or the abstract of the papers (wrong key word, e.g., throwing, growing, etc...) or irrelevant data analysis (not a correlative study). Sum of 57 papers was adopted for the full text screening, although only 51 papers were screened due to unavailable full texts. In some cases, the full text was obtained via the Research Gate scientific platform, or via direct email communication with authors. After full text screening we were left with 16 papers identified via databases that were included in this review.

Additionally, we identified 9 more papers through the snowball method; citation searching in reference list of primary included papers. These were studies that eluded the primary search and/or were not in the Scopus or Web of Science database. Out of the 9 additionally identified papers only one full text was unavailable. We therefore have 8 papers identified via secondary search methods included in this thesis, leading to the total sum of 24 scientific correlation-predictive articles that are assessed in this thesis.

All the screening was done solely by the author of this thesis. There is no external contribution of another author, although it would be warranted to validate the methodological approach and inclusion/exclusion criteria specified below.

4.7. INCLUSION CRITERIA

- Peer-reviewed journal publications
- Correlation-predictive papers
- Correlates fitness or anthropometrical variables directly to measured performance
- Either on-water or ergometer
- Published after year 2000
- Available full text

4.8. EXCLUSION CRITERIA

- Unavailable full text (if provided via direct communication with authors - acceptable)
- Variables are correlated to non-Olympic rowing (i.e., traditional rowing, coastal, etc...)
- Missing ethical committee approval

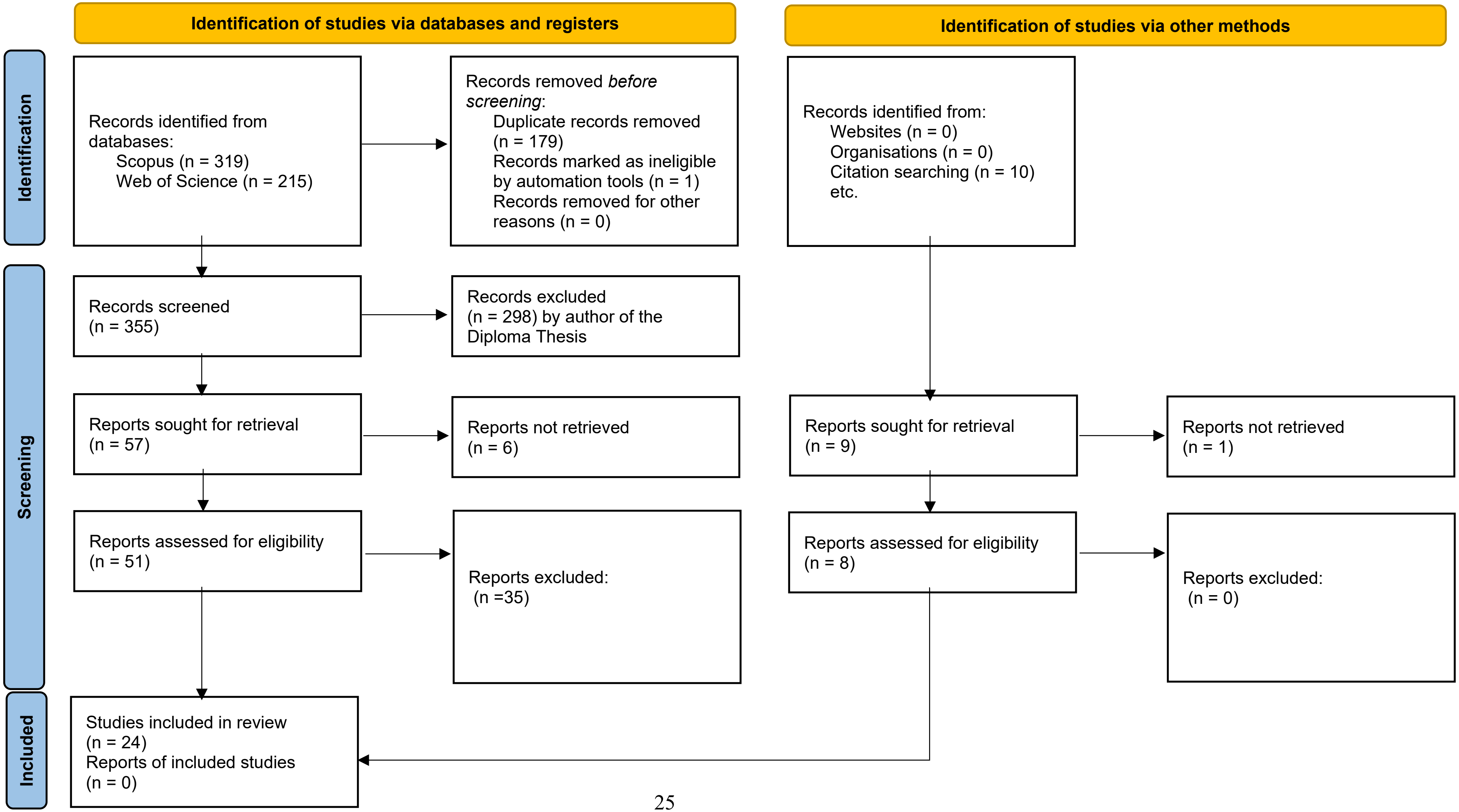


Diagram 1 - PRISMA diagram

Adopted from Page et al. (2021)

4.9. PREPARATION OF THE SUMMARY TABLES

The data from included studies are extracted into 3 main types of tables that include key information about the study.

The main overview table (Table 13) includes the author citation together with year of publication, information about the subjects in the study participant's sex, performance level and if necessary additional data about the group composition. Next column is the total (n) number of participants in the study. Performance type reports on the main type of performance that is observed within the study. Main finding, Notes reports the strongest correlating variables from the study together with other vital information.

To keep the table brief only the 3 strongest predictors are usually reported. If more than 3 strong predictors are found those predictors are than extracted to the separate table that includes variables that repeatedly (in more than one article) correlated, as reported by this thesis. The main overview table also includes the second table described below although for clarity it is also reported separated due to the size if the main overview table.

The second tables (Table 2 and 3) will report the strongest and the most frequently correlated variables with their exact coefficient of correlation. The variable in this table must be reported to have coefficient of correlation (r=>0,8) in any included study (at least one). This correlation limit is set by the author and is deemed to be expertly determined lower limit of valid prediction.

The last tables (Tables 4 - 12) are for the individual variables. There will be a separate table for each of the identified variables.

5. RESULTS

In total 24 studies that fully met the criteria specified in the methodology section of this thesis were identified. The correlation coefficients for specific variables were extracted from the studies (Table 13)

We identified 11 variables that were most frequently correlated with performance on ergometer or on the water (Table 2, Table 3) and had reasonably high correlation with said performance. These key variables are; Body Mass (kg) (Table 4), Lean Mass (kg) (Table 6), VO2Max (L/min) (Table 7), Power at VO2Max (W) (Table 8), Power at 4mml (W) (Table 9), Body Height (cm) (Table5), Wingate mean (W) (Table 10), Wingate maximal (W) (Table 10), Wingate minimal (W) (Table 10), Leg Press 1RM (kg) (Table 11), and 2000m ergo score (Table 12).

Several studies have reported variables with very high correlation, i.e. ($r>.9$). With over all highest correlation of ($r=.973$) in Lean Body Mass (kg) /Muscle Mass (kg) when associated with ergometer rowing. There are also controversial parameters with various strength of correlation across the reviewed papers.

The most frequently correlated parameter with rowing/ ergometer rowing performance is VO2Max (l/min) with total sum of 12 appearances.

Appeared X times	Study Variables										
	11	9	12	6	7	11	5	3	2	2	4
p ≤ 0,05	Body Mass (kg)	Lean Mass (kg)	VO2Max (L/min)	Power at VO2Max (W)	Power at 4 mml (W)	Body Height (cm)	Wingate mean (W)	Wingate maximal (W)	Wingate minimal (W)	Leg Press 1 RM (kg)	2000 m ergo Score
Akca 2014	-0,812	-0,822	X	X	X	-0,801	-0,796	-0,756	-0,778	-0,755	X
Barrett, Manning 2004	-0,87	X	X	X	X	-0,86	X	X	X	X	0,9
Bourdin et al. 2014	X	X	0,84	0,92	X	X	X	X	X	X	X
Cerasola et al. 2020	-0,815	X	-0,761	X	X	-0,877	-0,943	X	X	X	X
da Silva et al. 2020	X	X	X	X	X	X	X	X	X	X	X
Holway, Guerci 2012	X	X	X	X	X	X	X	X	X	X	X
Huang, Nesser 2007	-0,471	X	X	X	X	-0,837	X	X	X	-0,536	X
Jurimae et al. 2000	-0,910 -0,500	-0,910 -0,510	-0,760 -0,640	-0,970 -0,700	X	-0,770 -0,360	X	X	X	X	0,72
Lawton et al. 2013	X	X	X	X	X	X	X	X	X	X	X
Majmudar et al. 2017	-0,506	X	X	X	X	-0,34	X	X	X	X	X
Metz et al. 2018	X	X	-0,84	X	-0,82	X	X	X	X	X	X
Mikulič, Ružič 2006	X	0,77	0,87	X	0,91	X	X	X	X	X	X
Mikulič et al. 2009	X	X	X	X	X	X	X	X	X	X	X
Nevill et al. 2009	X	X	0,94	0,96	X	X	X	X	X	X	X

Table 2 - Study Variables and Correlation ½

p ≤ 0,05	Study Variables										
Appeared X times	11	9	12	6	7	11	5	3	2	2	4
	Body Mass (kg)	Lean Mass (kg)	VO2Max (L/min)	Power at VO2Max (W)	Power at 4 mml (W)	Body Height (cm)	Wingate mean (W)	Wingate maximal (W)	Wingate minimal (W)	Leg Press 1 RM (kg)	2000 m ergo Score
Reichman et al. 2002	-0,508	-0,723	-0,502	X	-0,822	-0,815	-0,87	-0,847	-0,89	X	X
Yoshiga, Higuchi 2003	-0,85	-0,91	-0,9	X	X	-0,81	X	X	X	X	X
Ingham et al. 2002	0,82	0,94	0,88	0,95	0,92	0,76	X	X	X	X	X
Mikulič 2009	-0,693	-0,767	-0,484	-0,732	-0,743	-0,257	X	X	X	X	X
Maciejewski et al. 2015	X	0,91	X	X	X	X	0,91	X	X	X	X
Penichet, Pueo 2017	0,894	0,973	X	X	X	0,873	X	X	X	X	X
Vogler ae atl 2010	X	X	0,95	X	X	X	X	X	X	X	X
Kendall et al. 2011	X	X	-0,923 -0,558	-0,866 -0,637	-0,549 -0,536	X	X	X	X	X	X
Mikulič et al. 2009	X	X	X	X	X	X	X	X	X	X	0,920 0,800
McNeely 2012	X	X	X	X	-0,267	X	-0,2	-0,229	X	X	0,12

Table 3 - Study Variables and Correlation 2/2

Body Mass (kg) and Body Height (cm) are the most common predictors of rowing/ergometer performance, both were included in 11 out of 24 reviewed studies. Both predictors were included in the same articles, they were reported on together. Body Mass (kg) correlation ranged (r=.471 - .910) with an average reported value around (r=.800). Body Height (cm) is correlated in a range (r=.257 - .877) with most common predictive strength in a range (r=.750 - .850).

$p \leq 0{,}05$	Body Mass (kg)
Akca 2014	-0,812
Barrett, Manning 2004	-0,87
Cerasola et al. 2020	-0,815
Huang, Nesser 2007	-0,471
Jurimae et al. 2000	-0,910 -0,500
Majmudar et al. 2017	-0,506
Reichman et al. 2002	-0,508
Yoshiga, Higuchi 2003	-0,85
Ingham et al. 2002	0,82
Mikulič 2009	-0,693
Penichet, Pueo 2017	0,894

Table 4 – Body Mass (kg) correlation

$p \leq 0,05$	Body Height (cm)
Akca 2014	-0,801
Barrett, Manning 2004	-0,86
Cerasola et al. 2020	-0,877
Huang, Nesser 2007	-0,837
Jurimae et al. 2000	-0,770 -0,360
Majmudar et al. 2017	-0,34
Reichman et al. 2002	-0,815
Yoshiga, Higuchi 2003	-0,81
Ingham et al. 2002	0,76
Mikulič 2009	-0,257
Penichet, Pueo 2017	0,873

Table 5 - Body Height (cm) correlation

Similarly, although with slightly stronger correlations reported, Lean Body Mass (kg) was another valid anthropometric performance predictor with 9 appearances among reviewed studies. Correlation of LBM (kg) ranged (r=.723 - .973) and it is reported to be above (r=.910) in 4 articles.

$p \leq 0{,}05$	Lean Mass (kg)
Akca 2014	-0,822
Jurimae et al. 2000	-0,910 -0,510
Mikulič, Ružič 2006	0,77
Reichman et al. 2002	-0,723
Yoshiga, Higuchi 2003	-0,91
Ingham et al. 2002	0,94
Mikulič 2009	-0,767
Maciejewski et al. 2016	0,91
Penichet, Pueo 2017	0,973

Table 6 - Lean Mass (kg) correlation

Out of the 11 variables there are 3 valid physiological determinants of rowing performance, but mostly ergometer performance; VO2Max (l/min), Power at VO2Max (W) and Power at 4 mml (W).

Strongest correlation is reported to be (r=. 970) with range (r=.484 - .970). VO2Max (l/min) is reported with (r>.800) in 8 articles out of 12 in which it was observed. It is also the most used performance predictor with said 12 cases.

$p \leq 0,05$	VO2Max (L/min)
Bourdin et al. 2014	0,84
Cerasola et al. 2020	-0,761
Jurimae et al. 2000	-0,760 -0,640
Metz et al. 2018	-0,84
Mikulič, Ružič 2006	0,87
Nevill et al. 2009	0,94
Reichman et al. 2002	-0,502
Yoshiga, Higuchi 2003	-0,9
Ingham et al. 2002	0,88
Mikulič 2009	-0,484
Vogler et al. 2010	0,95
Kendall et al. 2011	-0,923 -0,558

Table 7 - VO2Max (L/min) correlation

Power at VO2Max (W) is reported on in 7 articles with correlation ranging (r=.637 - .970). In 4 cases it reports very high association with (r>.920). Comparable results also show Power at 4mml (W) which was observed in 7 articles. Correlation bellow (r=.800) is reported in 3 out of 7 cases with correlation range being (r=.267 - .920). The lowest reported value is when correlated to on water single scull rowing.

$p \leq 0{,}05$	Power at VO2Max (W)
Bourdin et al. 2014	0,92
Jurimae et al. 2000	-0,970 -0,700
Nevill et al. 2009	0,96
Ingham et al. 2002	0,95
Mikulič 2009	-0,732
Kendall et al. 2011	-0,866 -0,637

Table 8 - Power at VO2Max (W) correlation

$p \leq 0{,}05$	Power at 4 mml (W)
Metz et al. 2018	-0,82
Mikulič, Ružič 2006	0,91
Reichman et al. 2002	-0,822
Ingham et al. 2002	0,92
Mikulič 2009	-0,743
Kendall et al. 2011	-0,549 -0,536
McNeely 2012	-0,267

Table 9 - Power at 4 mml (W)

Associations of rowing and/or ergometer rowing with Wingate test are observed in 5 articles, with specific variables being Wingate Mean Power (W), Wingate Maximal Power (W) and Wingate Minimal Power (W). In 4 out of 5 cases Wingate appears to be a satisfactory performance indicator with all correlations being above (r=.756). The only exception is when correlated on water single scull results, the predictive strength decreased to (r=.200) in Mean Power (W) and (r=.229) in Maximal Power (W).

p ≤ 0,05	Wingate		
	Mean (W)	Maximal (W)	Minimal (W)
Akca 2014	-0,796	-0,756	-0,778
Cerasola et al. 2020	-0,943	X	X
Reichman et al. 2002	-0,87	-0,847	-0,89
Maciejewski et al. 2016	0,91	X	X
McNeely 2012	-0,2	-0,229	X

Table 10 - Wingate variables (W) correlation

The only pure strength test/predictor that appeared twice in all analysed studies is Leg Press 1RM (kg) with correlations (r=.536) and (r=.755).

p ≤ 0,05	Leg Press 1 RM (kg)
Akca 2014	-0,755
Huang, Nesser 2007	-0,536

Table 11 - Leg Press 1 RM (kg) correlation

At last, the 2000m ergometer score is reported to have variable predictive strength with range (r=.120 - .920). Association between 2000m score and on water rowing was explored in 4 out of 24 included articles.

p ≤ 0,05	2000 m ergo Score
Barrett, Manning 2004	0,9
Jurimae et al. 2000	0,72
Mikulič et al. 2009	0,920 0,800
McNeely 2012	0,12

Table 12 - 2000m ergometer score correlation

Study information				
Study year	**Participants sex, level**	**n**	**performance type**	**Main finding, Notes**
Akca 2014	Male, collegiate	38	ergometer	Highest correlated (r>0.8) anthropometric variables were Lean mass (kg) (r=-.822), Body Mass (kg) (r=-.812) and Body Height (cm) (r=-.801) Several other anthropometric variables correlated with performance significantly (r>0.7) suggesting large body dimensions are beneficial for rowing performance. From Physiological parameters Wingate test mean power (W) was best single predictor with (r=-.796).
Barrett, Manning 2004	Male, elite 6lwt, 9hwt	15	single scull	Ergometer to on water performance correlated with (r=.900). Anthropometric variables had very strong correlation in Mass (kg) (r=-.870), Body Height (cm) (r=-.860) and Strength (N) (r=-.840). Fastest rowers tend to be largest and strongest.
Bourdin et al. 2014	Unknown, elite 23lwt, 31hwt	54	ergometer	Best physiological predictor was Ppeak (W) (r=.920) and absolute VO2max (l/min) (r=.840) during incremental test. Body mass (kg), correlated at (r=.650); strongest from observed anthropometrical parameters.
Cerasola et al. 2020	Male, boys	15	ergometer	Height (cm) (r=-.877) was the best anthropometrical predictor and absolute VO2Max (ml/min) (r=-.761) together with Wingate Mean Power (W) (r=-.943) were highest correlating physiological predictors.
da Silva et al. 2020	Mix, juniors elite 11 female 15 male	26	single scull	Different correlations in male and female with moderate correlations in all monitored aspects. On water competition times were converted into ranking order which might have influenced the final correlation coefficient. Suggest different predictors for male and female category. No physiological or anthropometrical correlation reported

Holway, Guerci 2012	Mix, adolescents 58 female 56 male	114	ergometer	Low to moderate correlations in both genders. Strongest correlation in female was Arm Muscle ar. (cm2) (r=-.636) and Sitting Height (cm) (r=-.615). In male Height (cm) (r=-.647) and Arm Span (cm) (r=-.640) had the highest correlation.
Huang, Nesser 2007	Mix, adolescents 10 male 7 female	17	ergometer	Height (cm) (r=-.837) and Vertical Jump (cm) (r=-.736) is reported as high correlate of ergometer performance, although genders are combined within the analysis due to the small sample size.
Jurimae et al. 2000	Male, experienced	10	ergometer and single scull	Several parameters show very high (r>0.9) correlation with ergometer performance; Body mass (kg), Lean Body Mass (kg), Maximal Aerobic Power (W), Anaerobic threshold (W) and LA concentration at 350W (mmol/l). For on water performance the best predictors were VO2Max (l/min), Maximal Aerobic Power (W) and rowing economy (i.e., LA350W) with moderate predictive value (r=.640 - .700).
Lawton et al. 2013	Male, elite	19	ergometer	A moderate correlation with 2000m ergometer performance was observed in Concept 2 Dyno in Leg Press 5RM (W) (r=-.690). Seated Arm Pull 60RM (W) (r=-.660), Power Clean (kg) (r=-.630) and Bench Pull 6RM (kg) (r=-.680). Correlations were also made in relation to other ergometer test distance (i.e., 500m, 5000m, 60 min, and Peak Power (W)). With shorter distance the correlation increased opposed to longer test where the correlation decreased. In both cases generally staying within the moderate correlation range.
Majmudar et al. 2017	Male, elite 139lwt, 60hwt	199	ergometer	Highest correlation was observed in Body Mass (kg) (r=-.506) and Back Strength (kg) (r=-.458). Study presents correlations of very few parameters but on a large research sample. Performance level is presented as elite but a closer look at the parameters suggests club - national level (from a European rowing standpoint)
Metz et al. 2018	Mix, University 4 female 8 male	12	ergometer	Very high correlation was observed in Maximum power/stroke (watts/stroke) (r=-.960) and Power/stroke at VT2 (watts/stroke) (r=-.896). High correlation was observed in Maximal oxygen uptake (L/min) (r=-.840) and Oxygen uptake at VT2 (R=-.820). Study does not differentiate between male and female rowers.
Mikulič, Ružič 2006	Male, adolescent	48	ergometer	Multiple parameters correlated highly (r=.7 - .9) with 1000m rowing ergometer competition time; Body Height (cm) (r=-0.790), Lean Body Mass (kg) (r=-.820), VO2Max (l/min) (r=-890) and VO2 at Anaerobic Threshold (L/min) (r=-.870). Several other anthropometric and physiological parameters showed moderate predictive strength.

Mikulič et al. 2009	Mix, elite 157 hwt female 50 lwt female 246 hwt men 176 lwt men	638	Rowing disciplines	Highest correlation was reported in lightweight men’s single sculls (r=.780), women’s single sculls (r=.750), men’s single sculls (r=.720), and lightweight men’s double sculls (r=.720). This indicates higher predictive value of ergometer scores in small rowing disciplines. Other disciplines have mostly low to moderate correlations (r=.300 - .700)
Nevill et al. 2009	Mix, elite 21 hwt female 7 lwt female 33 hwt men 15 lwt men	76	ergometer	Best single physiological predictor for the whole group was Power at VO2Max (W) (r=.960). All observed physiological predictors related to power and oxygen consumption correlated very highly (r≥.900) with mean ergometer rowing speed over 2000m. There is a different predictive strength in observed parameters for individual genders with Power at VO2Max (W) (r=.920 female, r=.840 male) still being the best single predictor.
Reichman et al. 2002	Female, competitive	12	ergometer	The strongest anthropometric predictors with high predictive strength were Height (cm) (r=-.815) and Lean Mass (kg) (r=-.723). Mean power (W), Peak power (W) and Minimal power (W) in 30s Wingate test correlated highly with 2000m ergometer performance with (r≥-.850).
Yoshiga, Higuchi 2003	Mix, unknown 71 females 120 males	191	ergometer	Rowing performance was correlated to Body Height (cm) (r=-.810), Body Mass (kg) (r=-.850), Fat Free Mass (kg) (r=-.910), and VO2Max (r=-.900). Individuals with large body size and aerobic capacity possess an advantage for a 2000-m row on an ergometer.
Ingham et al. 2002	Mix, elite 13 hwt female 5 lwt female 19 hwt men 4 lwt men	41	ergometer	The strongest correlations for the group regardless of gender were reported for Power at VO2Max, Maximal Power (W) and Maximal Force (r=.950). There is a different predictive strength in observed parameters in both genders with Power at 2 and 4 mmol of LA having very high predictive value.
Mikulič	Male, international	25	ergometer *6000m	The strongest anthropometric predictor was Lean Body Mass (kg) (r=-.767). From physiological variables the strongest correlation was observed in Power Output at Ventilator Threshold (W) (r=-.743) and Power at VO2Max (W) (r=-.732)
Maciejewski et al. 2016	Unknown, adolescent	14	ergometer *1500m	Very high correlation was reported in Mean 30 sec Wingate Power (W) (r=.910)
Penichet, Pueo 2017	Mix, elite 11 female 11 male	22	ergometer	Performance and efficiency in rowing ergometer test strongly correlated with anthropometric characteristics of height (r=.873), weight (r=.894), body muscles (r=.973). Study also provides leg strength predictors.

Vogler et al. 2010	Male, international	7		Authors correlate physiological variables to both ergometer and on water performance. VO2Max correlates with rowing performance at (r=0,940) and ergometer performance at (r=0,960).
Kendall et al. 2011	Female, collegiate	35	ergometer	Study provides data on novice level and varsity level (advanced) performers. Critical velocity test was solid predictor in both groups. Strongest predictor in advanced group was VO2Max (l/min) with very high correlation (r=.923) and Peak Power (W) also being highly correlated (r=.866).
Mikulič et al. 2009	Mix, juniors elite	398	Rowing disciplines	Final rank from Junior World Rowing Championship is correlated to their individual ergometer score. Correlations are strongest in smaller boats i.e., female single (r=.920), male single (r=.800). For larger boats i.e., fours and eight correlations ranged between (r=.310 - .700).
McNeely 2012	Male, elite	19	single scull	Study concludes ergometer testing is not a valid choice of test due to the low correlation with on water single scull performance. (r=.120). Study results show mediocre (low to negligible) predictive strength of physiological variables.

Table 13 - Study information

6. DISCUSSION

After conducting the review, this thesis has provided a several important rowing performance and ergometer performance indicators. It is however reported by majority of reviewed articles, that single predictor assessment is not optimal way of selecting athletes. Of course we fully agree on this matter but there is a need to identify even these single predictors in order to build more sophisticated performance prediction equations. The issue with these equations in practise is however their complexity a difficulty of interpretation to regular coaches. In our experience this means that they are very scarcely used in real rowing environment and that they stay predominantly in the academic sphere and scientific environment. Since majority of the included articles covers both a single predictors and predictive equations, we also had a brief glance at this and were left with more questions than answers since the great variability of included parameters (which is also illustrated by the results of this review). There is no clear consensus still both in single predictors are and thereby probably even more so in the predictive equations since those are based on the single predictors.

There are several matching pieces among the presented studies; VO2Max for example appears to be very solid predictor regardless of the category and performance level of the participants as illustrated by our report and findings of most included articles. There are however cases (Mikulič 2009; Kendall et al. 2011; Riechman et al. 2002) where even the correlation of this variable is in the area of average correlation ($r= \pm.5$) which with a sample size of tens of participants can hardly be considered a strong predictor. There is always a need for some skepticism, although looking at this even through absolutely nonscientific optics there must be something about it since VO2Max (L/min) appeared in nearly half of the articles included. And there is! VO2Max was not the only variable that had “good results”.

There is a pattern emerging here where all the variables associated with power or oxygen consumption as well as power and oxygen consumption appears to be strong predictors this goes for Power outputs at VO2Max same as Power at 4 millimolar lactate concentration. There is limitation here which comes from the way of understanding theoretical concept of anaerobic threshold which is associated (among other physiological changes) with the onset of blood lactate accumulation of 4 millimols (Yoshida et al. 1987; Ghosh 2004). The blood lactate accumulation is only one of the possible physiological parameters by which to assess the anaerobic threshold. During the screening of the articles, a discrepancy was found in the nomenclature used regarding the anaerobic threshold where in some cases it was referred as 4 millimols power, in other cases as second lactate or ventilator breakpoint. All of these terms refer to the theoretical concept of anaerobic threshold and within this review they are all united under one variable. As was previously mentioned, it was not always possible to determine the exact method of determining the anaerobic threshold in the reviewed studies. We believe that the 4 mml reference lactate concentration should not be used for determination of anaerobic threshold, since the breakpoint can occur at lower or higher individual lactate concentration; 3 – 6 mml of blood lactate (Radák 2018). In practice incorrect determination of training zones can lead to mistakes in the management of the training process and possibly to overreaching and overtraining. This is not a direct topic of this thesis, however since we have already touched on this, we would like to urge some caution regarding taking over this perhaps outdated reference value to training practice.

With regards to Body Mass and Lean Body Mass variables were reported with similar correlations. We believe that this is due to the fact the predominant portion of the research is done on active population with already low body fat percentage. When both parameters were included in the article, there usually was a stronger correlation reported in Lean Body Mass with marginal difference (r=.812 BM, r=.822 LBM) (Akca 2014) but also larger difference (r=.508 BM, r=.723 LBM) (Riechman et al. 2002). Lean Body Mass appears to be very solid predictor of performance with correlation dropping below ($r<.7$) in only one case (Jurimae et al. 2000). It is interesting that LBM explains significant portion of rowing performance when relative value of VO2Max does so significantly less, since we know that with decrease in weight while maintaining the absolute VO2Max value increases the relative value of VO2Max (ml/kg/min). Probably this has to do with exponential drag of the water on the boat with increasing propulsive power expenditure. A rower's speed, therefore, should be proportional to the cube root (0.33) of power expended (Nevill et al. 2011). Rowers do not benefit that much from the relative weight to performance values (Grasgruber, Cacek 2008).

We were suprised by the small occurence of stregth predictive test among reviewed articles, although some did include stergth testing; Akca (2014) and Huang and Nesser (2007). Stregth variables for testing lower limb stregth were observed as the means of one reprtition maximum in leg press. It can be argued that there is some strength component incorporated into the wingate testing that occured several times. Escpecially the maximal Wingate power could be also interpreted as strength variable although Wingate test itself is a mean to determine the anaerobic power. Interestingly enough all the articles in this review used a form of modified Wingate test protocol, usually a 30 second form. With regards to the correlation strength of Wingate test and rowing ergometer performance it was surprising to us why maximal and minimal values were not reported in some articles (Cataldo et al. 2015; Maciejewski et al. 2016) since they apparently are valid predictors (Akça 2014; Riechman et al. 2002). It is also needles to note the huge dispute reported by McNeely (2012) where correlation of both maximal and mean Wingate power was below ($r<.229$). This makes a slight stain on the otherwise strong correlation of Wingate variables and warrants further investigation. The statistical significance was met at ($p \leq 0.05$) in McNeely´s study we cannot therefore dismiss his findings.

Before, the last variable that we need to mention in association with rowing is of course body height. Without worrying about the absolute or limit values of body height, in 7 out of 11 articles it was reported with high correlation ($r>.700$). In a nutshell this means higher equals better. The research problematic of rowers´ body height is from our point of view already exhausted. There are articles that are thematically repetitive with regards to body height and recent study (Busta et al. 2023) should put a pause on this topic at least for one Olympic quadrennium. At this point we believe there is no need to further look into body height in rowing with regards to both its absolute value and predictive strength.

Lastly, we need to talk about the relationship between the simulated 2000m ergometer race and on-water rowing. This topic always brings a lot of heat in the rowing environment and there is continuous discord. McNeely (2012) is very clear about his stance, illustrated by the negligible correlation of ($r=.120$) among elite athletes, however it is rare to find such a low correlation among other articles. Mikulič et al. (2009) reports strong correlation of ergometer to on water rowing in small boats ($r=.800$ junior males, $r=.920$ junior females) but small correlation in larger boats (4x-) ($r=.310$ junior males, $r=330$ junior females). Such a report goes directly against general beliefs that large boats need strong ergometer athletes. The correlation drops even to lower values when looking at senior elite rowing. For the elite quads this is ($r=.390$ males, $r=.020$ females) copying the trend also in sing scull but with much lower correlation strength ($r=.720$ males, $r=.750$ females). Interestingly enough in the heavy weight coxed pair and light weight coxless pair the correlation was reported negative, suggesting that better ergometer score might actually hurt the on-water performance. We do not believe that this is actually true in practice, neither do the authors of the article, but the data analysis and statistics suggest so. There might also be a difference between predictive strength of ergometer rowing among single scull specialists and rowers that aren't as proficient on a single scull.

The articles included in the review followed similar methodological approach, although in some cases, not all procedures are replicable due to the lacking information on the participants, test, or specific evaluation method of a test.

With regards to the methodology of this thesis we tried to follow PRISMA guidelines, especially during triage and screening of studies. This thesis however is not a pure systematic review in a PRISMA way. We incorporated our own ideas and methodological steps.

Ideally, we would search broader range of scientific databases EBSCO – SportDiscus and PubMed, since we discovered additional studies outside the primary screening of databases Scopus and Web of Science. This was covered by additional methodological approach (reference list screening – snowball method) it is however entirely possible that there are articles that eluded our search. We believe that the selected databases provided sufficient number of scientific papers for a diploma thesis type of work. Also we leave some room to human error here even though we strived to minimize it. All the screening was done by the primary author of this thesis and even though the screening was done repeatedly, and we believe that it was conducted diligently it is possible that an article might have been missed.

Inspiration for this thesis was drawn from the previous review articles by Smith and Hopkins (2012) and Lawton et al. (2011).

Additionally we were surprised by the lack of correlation predictive studies of on water rowing with any testing variables. We were able to find only 4 articles that covered this topic since year 2000. The rowing ergometers are used as an equal substitution for on water rowing even though it does not adequately address the skill component of rowing as reported by Smith and Hopkins (2012).

This is also future research direction we recommend. Better and broader studies on predictive variables for on water rowing could significantly improve selection process. We can expect valid predictive variables to change due to the shortening of the competition distance for 2028 Los Angeles Olympiad. Mimicking the nature of the sport as closely as possible in any type of research will improve the quality of findings. Ideally, we would recommend that all further research be conducted with a view of a shortened racecourse for the 2028 Olympics. Finding valid predictors for 1500m race might be The Topic in upcoming years.

7. CONCLUSION

From the total of 24 articles reviewed in this diploma thesis we identified 11 variables that were most frequently correlated with performance on ergometer or on the water and had reasonably high correlation with said performance. Strongest predictors (correlate) of rowing ergometer performance, based on the strength of correlation and frequency of occurrence in reviewed articles are; Body Mass (kg), Lean Mass (kg), VO2Max (L/min), Power at VO2Max (W), Power at 4mml (W), Body Height (cm), Wingate mean (W), Wingate maximal (W), Wingate minimal (W), Leg Press 1RM (kg), and 2000m ergo score. It is not recommended to base performance assessment on just single variable and/or make exclusion/inclusion decisions based on testing a single parameter, which is in agreement with previous finding of all reviewed articles.

Due to the high correlation of several variables we can state that reliance on a single predictor may lead to inaccurate assessment and that in rowing it is possible to compensate for lacking performance in one test variable by exceptional performance in another.

We believe that this problematic is still insufficiently explored; hence future research should focus on a search of other performance predictors than what is cover in this thesis. Also, there is a general lack of predictive studies for on water rowing. Additionally with the shortening of the regatta distance for 2028 Los Angeles Olympiad, there is a need to revisit current predictive dogmas with the new race distance in mind.

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