

Misuse of “Power” and other mechanical terms in sport and exercise science research

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1 Misuse of "Power" and other mechanical terms in Sport and Exercise Science Research

2

3 **Abstract**

4 In spite of the Système International d'Unités (SI) that was published in 1960, there
5 continues to be widespread misuse of the terms and nomenclature of mechanics in
6 descriptions of exercise performance. Misuse applies principally to failure to
7 distinguish between mass and weight, velocity and speed, and especially the terms
8 "work" and "power." These terms are incorrectly applied across the spectrum from
9 high-intensity short-duration to long-duration endurance exercise. This review
10 identifies these misapplications and proposes solutions. Solutions include adoption of
11 the term "intensity" in descriptions and categorisations of challenge imposed on an
12 individual as they perform exercise, followed by correct use of SI terms and units
13 appropriate to the specific kind of exercise performed. Such adoption must occur by
14 authors and reviewers of sport and exercise research reports to satisfy the principles
15 and practices of science and for the field to advance.

16

17

18 1. **INTRODUCTION**

19 The French philosopher and Nobel Laureate André Gide (1869-1951) is reputed to
20 have begun talks he gave with the following extract from his 1950 publication

21 Autumn Leaves:

22

23 *Everything's already been said, but since nobody was listening, we*

24 *have to start again.*

25

26 Sport and exercise science is the *scientific* study of factors that influence the ability to
27 perform exercise (also known, according to circumstances, as physical activity) as
28 well as the resulting adaptations. This study is directed principally at humans but it is
29 also applicable to equine, canine, avian, and other animal contexts. Importantly,
30 terms and nomenclature used to describe exercise should abide by the Système
31 International d'Unités (SI) i.e. be simple, precise, and accurate. The SI system

32 comprises seven base units, prefixes and derived units (Table 1). This enables
33 scientists from different disciplines to communicate effectively (24) and germane here,
34 to advance sport and exercise science. With Institutional ethics approval, the purpose
35 of this review is to highlight principally how "power", but also other SI mechanical
36 variables, are misused in many exercise science research reports and then indicate
37 correct use of terms and nomenclature that best describe and evaluate exercise
38 performance. The review will define exercise and then proceed to examine misuse of
39 mass and weight, work, velocity, power, and efficiency. For all physical activities
40 Newton's Second Law will be demonstrated as the fundamental mechanical
41 relationship used to document the causes of performance. A case will be made to
42 abandon the phrase "critical power" and adopt instead "critical intensity" for the
43 otherwise laudable concept of tolerance to exercise. Finally, a recommendation will
44 be made to ensure that if sport and exercise science research is to be recognised as an
45 established and credible area of application of science and so advance, terms and
46 nomenclature to describe the performance of exercise must abide by principles of
47 mechanics laid down by Newton and in turn, use the SI.

48

49 2. **EXERCISE**

50 For military, occupational, and within the last two hundred years or so, sport-, leisure-
51 related, health and quality-of-life reasons, the need to quantify either total exercise
52 accomplished or the effectiveness with which exercise is performed has been a
53 principal focus. This focus continues.

54

55 The World Health Organisation defines exercise as:

56

57 *A subcategory of physical activity that is planned, structured,*
58 *repetitive, and purposeful in the sense that the improvement or*
59 *maintenance of one or more components of physical fitness is the*
60 *objective.* (<http://www.who.int/dietphysicalactivity/pa/en/>).

61

62 Exercise can also be defined as:

63

64 *A potential disruption to homeostasis by muscle activity that is*
65 *either exclusively or in combination, concentric, isometric or*
66 *eccentric.*

67 (33).

68

69 Only one of these definitions (33) acknowledges that either deliberately or out of
70 necessity, gross external movement is not always a primary outcome. Where
71 accelerated movement does occur, the activities are dynamic. Where it does not, the
72 activities are static. Examples of the latter are the primarily isometric muscle actions
73 in balance, a yoga pose, or in gymnastics, strength poses such as the crucifix on rings.

74

75 In some sports such as gymnastics, and weight-lifting, movement after completion of
76 dismount or lift is undesirable and is penalised by the judges or referees. In others
77 such as archery and shooting, stillness is crucial for performance (34). Even in
78 dynamic sports such as luge, skeleton bobsled and swimming, the ability to hold
79 streamlined positions of the body is decisive

80 ([http://www.geomagic.com/en/community/case-studies/british-team-uses-geomagic-](http://www.geomagic.com/en/community/case-studies/british-team-uses-geomagic-3d-reverse-engineering-to-streamline-/, 9)81 [3d-reverse-engineering-to-streamline-/, 9](http://www.geomagic.com/en/community/case-studies/british-team-uses-geomagic-3d-reverse-engineering-to-streamline-/, 9)). Similarly, in sailing, the ability to

82 maintain high-force, isometric muscle activity for prolonged durations is crucial. In
83 scrums in Rugby Union, 16 players can be primarily exercising isometrically for 10 s
84 or so with maximal effort, yet minimal external movement occurs. Even in dynamic
85 activities such as running and swimming, stabiliser and fixator muscles act either
86 actually or quasi isometrically. Moreover, many activities of daily living require little
87 or no movement (e.g. maintenance of posture, supporting objects in domestic tasks,
88 screwing the tops on jars until tight and maintaining yoga poses).

89
90 While the ability of muscle to exert force in a discrete task is important, the ability
91 repeatedly to exert force (i.e. sustain exercise in endurance activities), is equally
92 important. Effective endurance performance requires an ability to delay the onset of
93 fatigue - taken here to be "any reduction in force-generating capacity (measured as
94 maximum voluntary muscle action), regardless of the task performed" (5).

95

96 3. **QUANTIFYING THE ABILITY TO PERFORM EXERCISE**

97 Precise quantification of exercise is an integral part of research to improve our
98 knowledge and understanding of factors that influence the ability to perform exercise.
99 However, there is a key confounding factor that traps the unwary: human and other
100 animal bodies are not simple, rigid systems. They are complex, multi-segment
101 systems and muscular performance does not always result in movement. Even where
102 movement does occur and in spite of concerns expressed by many (1, 17, 18, 24, 27,
103 30, 33), exercise science researchers frequently misapply classical mechanics
104 presented by Newton in 1687 in his three-volume *Philosophæ Naturalis Principia*
105 *Mathematica* (Mathematical Principles of Natural Philosophy). Misapplications are
106 most common for the mechanical variables “work”, “velocity”, “power” and

107 “efficiency”. These terms have strict definitions in Newtonian mechanics, the SI, and
108 exercise science (17, 24, 25), yet frequently, they are used incorrectly. The use of
109 incorrect, vague, and colloquial meanings of standardized mechanics terms creates
110 numerous problems for readers and the field of exercise science. For instance,
111 imagine a multi-disciplinary collaboration where a nutritionist, coach and sport
112 psychology consultant want to use the same word “power” for different things when
113 working with an athlete. The nutritionist uses power to describe the rate of transfer of
114 chemical energy from food, the coach uses "quick power" and "long power" to
115 describe energy systems in sport and the psychologist uses power to describe the
116 mental energy/focus on the task at hand. How do these people communicate? How
117 does the athlete understand them or integrate their advice with the strength and
118 conditioning coach who talks about "power output" in sport? The answer to these
119 questions is simple: "With great difficulty and not according to the principles of
120 science".

121
122 Abuses also include use of “workload” (18, 31, 33) and "work rate" (24). Moreover,
123 the important and highly relevant impulse-momentum relationship that expresses
124 Newton’s second law is frequently overlooked. In spite of the publication in 1960 of
125 the SI that was intended to standardise terms, units and nomenclature, there continue
126 to be misapplications, irregularities and transgressions in expression in exercise
127 science research`. These include failures to distinguish between variables as basic as
128 mass and weight.

129

130 4. **MASS AND WEIGHT**

131 Mass is the amount of matter in a body. The unit in which this amount is quantified
132 and expressed is the kilogram (kg). Weight is the force that results from the action of
133 a gravitational field on a mass (24). It is expressed in the eponymous unit, the newton,
134 named after Sir Isaac Newton. The symbol is N.

135
136 If body weight is reported, it should be expressed in newtons. Yet, frequently in high-
137 ranking journals, even those that have "science" in their title, published manuscripts
138 allow expression of body weight in kg. Similarly, in friction-braked cycle ergometry,
139 external resistance is sometimes expressed in kg or as a percentage of body mass. In
140 both instances, this is simply incorrect, because since resistance is a force, it should be
141 expressed in N or as a percentage of body weight. Use of the term "resistance" in
142 strength and conditioning usually implies gravitational resistance, although elasticity
143 of tissues and structures could also be involved, so the direction (vertical) required of
144 a vector quantity like force is accounted for.

145

146 5. MECHANICAL WORK AND POWER

147 For dynamic activities, mechanical work is what is done when:

148

149 *A force moves its point of application such that some resolved part of*
150 *the displacement lies along the line of action of that force.*

151 (33).

152

153 The unit in which work is expressed is eponymous, the joule, named after the
154 physicist and English brewer James Prescott Joule (1818-1889). It is an SI
155 derived unit, has the symbol J and is defined as what is done when:

156

157

A force of one newton moves through a distance of one metre.

158

159

Work is usually calculated as N·m.

160

161

Power is defined as:

162

163

The rate of performing work.

164

(24).

165

166

The unit is also eponymous: the watt, symbol W. It is named after the Scottish

167

mechanical engineer James Watt (1736-1819). It should be made correctly as a mean

168

value for some duration, although instantaneous power flows can be calculated.

169

However, power flows so calculated can vary widely and are strongly influenced by

170

the model and data used to calculate power (17). If interpretation is to be meaningful,

171

selection of duration must be made with care.

172

173

Similar to time (s), speed ($\text{m}\cdot\text{s}^{-1}$), and temperature (K), both work (J) and power (W)

174

are scalar quantities. Scalars possess magnitude but not direction, as opposed to

175

vector quantities such as velocity, force and change of temperature that possess both.

176

The use of the term “power” in exercise science research reports should be used

177

correctly, so the context must satisfy its strict requirements and be appropriate to

178

documenting performance. For example, in cycle ergometry, exercise science research

179

reports should refer to the mean external power output. This is because the ergometer

180 does not measure the energy used to accelerate the performer's limbs or the energy
181 wasted in impulses applied to the pedals in non-propulsive directions.

182
183 In exercise, forces are exerted by skeletal muscles that create moments of force which
184 tend to rotate joints (23). The function of skeletal and other types of muscle is to
185 exert force, and they do so by attempting to shorten. If the attempt is successful,
186 concentric muscle activity occurs. If the overall muscle-tendon unit remains the same
187 length, the activity is said to be isometric. When muscle is lengthened while it is
188 exerting force, the action is called eccentric. Swammerdam's experiment some 300
189 years ago, cited in Needham (22), demonstrated clearly that when active, muscle does
190 not decrease in volume. Hence, and as Rodgers and Cavanagh (24) indicated, the
191 expression "muscle contraction" is simply wrong and at best inexact; it is not
192 scientific. Cavanagh (6) therefore advocated that the phrase "muscle action" is the
193 most accurate term for use in exercise science.

194
195 For muscle to exert force, chemical energy is required. Principally, this is supplied
196 from forms of carbohydrate, fat, and protein but metabolism and accompanying
197 biochemical reactions release the energy that allows muscle to function. The currency
198 of this energy is adenosine triphosphate (ATP) and related high-energy phosphagens.
199 The challenge during exercise is to meet required energy demands and so synthesise
200 and re-synthesise ATP.

201
202 Against this brief background, consideration can now be given to correct the
203 erroneous use of scalar and vector mechanical variables to describe exercise
204 performance.

205

206 6. **SIMPLE MEASURES**

207 The simplest forms in which exercise can be quantified are distance (m) and time (s)
208 required for movement. In running events, overall performance is often accurately
209 described by time. These types of event could also be investigated by converting this
210 time and distance information into the scalar quantity speed. Speed though, is not
211 synonymous with velocity. In a 10,000 m race on a 400-m track the mean velocity is
212 zero since athletes finish where they started. The same applies in swimming in 50-m
213 pools for events such as 100 m, 200 m and 1500 m.

214

215 If performance is to be expressed as work, there must be some measureable and
216 meaningful quantification of joules produced. For example, this cannot occur in
217 isometric muscle activity where no notable body movement occurs. Similarly, when
218 activities are recorded as distances covered by players in field games such as
219 Association Football, codes of rugby, and court-based games, the use of "joules"
220 cannot occur. Nevertheless, these types of activity can and often do require
221 considerable expenditures of energy.

222

223 7. **THE IMPULSE-MOMENTUM RELATIONSHIP**

224 This relationship is fundamental to all activities in sport and exercise because it is
225 Newton's Second Law. The *Principia* stated, although the original was in Latin:

226

227 *The change of momentum of a body is proportional to the impulse*
228 *impressed on the body, and happens along the straight line on which*
229 *the impulse is impressed.*

230

231 This law of motion, so expressed or in the instantaneous version ($\Sigma F = ma$ where m is
232 the system mass and a a centre of mass acceleration) documents the mechanistic cause-
233 effect of how forces modify motion. The vector nature of forces, impulses,
234 acceleration, and momentum means that these calculations are performed in defined
235 directions relevant to documenting the motion.

236

237 The law can be expressed mathematically as follows (33):

238

$$239 \quad F \propto a$$

240 where: F is the mean force and a is the resulting mean acceleration.

241

242 By introducing a constant, m , the proportionality expression can be changed into an
243 equation:

244

$$245 \quad F = m \cdot a$$

246 where: F is mean net force and m is the mass of an object.

247

248 Acceleration, a , is the rate of change of velocity so the equation can be expressed as:

249

$$250 \quad F = m \cdot ((v - u)/t)$$

251 where: v is final velocity, u is initial velocity and t is the duration over which the
252 change occurs. This can be rearranged to:

253

$$254 \quad F \cdot t = m \cdot v - m \cdot u$$

255 where: $F \cdot t$ is the impulse of the force and $m \cdot v - m \cdot u$ is the change of momentum of the
256 body, hence the name: the impulse-momentum relationship.

257

258 For an activity such as vertical jumping in which initial velocity, u , is 0, the
259 expression becomes:

260

$$261 \quad Ft = m \cdot v$$

262 In a vertical jump, there is a, vertical reaction force, R , that acts upwards and a weight,
263 mg , that acts vertically downwards. In the above formula, the net force F , = $R - mg$.

264

265 Rearrangement of the equation allows the velocity of the body at departure or release
266 to be identified:

267

$$268 \quad (F \cdot t) / m = v$$

269

270 This relationship is precise, mathematically irrefutable and describes not only
271 requirements for performance but importantly, also explains pre-requisites for
272 performance.

273

274 For projectile activities in which an object is thrown, kicked, struck with an
275 implement such as a racket or stick, or when the projectile is the body as in horizontal
276 and vertical jumping, it is the velocity of the mass centre at departure or release and
277 the mass centre location in space that determine trajectory (1). The vector nature of
278 velocity documents both magnitude (speed) and direction of the object's initial motion

279

280 Hence, the object could be propelled at great speed or alternatively, at low speed with
281 delicacy as for instance a drop-shot in racket-sports. Neither high nor low speed is
282 effective without accurate direction. It is the impulse applied to the object by the
283 performer either directly or with the assistance of an implement that enables the
284 performer to defeat their opponent. In these cases, claims that a racket or performer is
285 powerful are misuses of terms. In fact, the performer or racket may be said to be
286 impulsive.

287
288 Effective technique requires the integration of several factors so as to optimise
289 impulse in the appropriate timing and direction for a movement task. For example,
290 large forces are required but if they are too large, injury to muscle or tendon and in
291 extreme cases, bone, could occur (12). When optimising throwing technique to
292 maximise distance thrown in events such as shot-put, discus and javelin, the duration
293 of contact with the implement before its departure is an important measure. Similarly
294 in jumping, techniques are designed to capitalise on duration of contact with the
295 ground immediately before departure into the air (3). These durations must provide a
296 compromise of numerous factors including the jump goal, preparatory motions, and
297 exploitation of neuro-muscular properties using eccentric-to-concentric stretch-
298 shortening cycle muscle actions (19).

299
300 The ability to develop impulse is also important in field games such as rugby,
301 association football, and field- and ice-hockey as well as court-based games such as
302 tennis, squash, and basketball. Players either have to outwit opponents with swerves
303 or "cuts" (side-steps) or change direction rapidly to reach a ball or avoid a tackle.
304 Such movements require changes in velocity i.e. where both speed and direction are

305 deliberately changed. Changes in these properties are determined by a generated
306 impulse.

307
308 The words “power” and “explosive” are ubiquitously applied in research and
309 professional practice to tasks that are brief and require maximal neuromuscular
310 activation such as jumps, strikes, kicks and throws, as well as weightlifting and
311 resistance training (17). This is in part driven by the proliferation of inexpensive and
312 easy-to-use systems to assess kinematics and kinetics during these movements,
313 particularly in the field of strength and conditioning. Such devices produce an array
314 of variables, some of which are measured directly and others derived based on
315 Newtonian physics. However, they are often poorly defined, are not valid, or simply
316 do not represent the performance being assessed. Of particular concern is use of the
317 word “explosive”. This is not a physics term and of course nothing actually “explodes”
318 in the human. We recommend that the term “explosive” no longer be used to describe
319 human movement.

320
321 “Power” is often expressed as a “clearly defined, generic neuromuscular or athletic
322 performance characteristic” rather than as an application of the actual mechanical
323 definition (17) which leads to considerable inaccuracy and confusion. We reiterate
324 that maximal neuromuscular efforts have the goal of maximising the impulse
325 produced as this determines the resulting velocity as a result of the impulse-
326 momentum relationship. Humans with inherent or developed abilities in such
327 movements would be more accurately described as “highly impulsive” and the most
328 appropriate measure of such performance is the impulse they produce. To reinforce
329 the point, power is a scalar quantity with both peak and mean measures poorly related

330 to jumping or throwing performance compared with resultant force or impulse that
331 predominantly dictate the performance outcome.

332
333 So far, the focus has been on discrete actions but in many sports and activities, actions
334 are not discrete i.e. they do not occur only once, they have to be performed repeatedly;
335 for hours in the case of tennis and marathon running. This leads to consideration of
336 effective impulse in endurance activities.

337

338 8. **ENDURANCE ACTIVITIES: REPEATED IMPULSES**

339 In endurance activities such as long-distance cycling and running, it is the ability
340 repeatedly to generate impulse that is decisive. In cycling, force by each leg is
341 applied that creates an angular impulse which drives the rotation of the pedals and the
342 drive mechanism of the bicycle. In one revolution of the pedal crank, two such
343 impulses are applied. This contrasts with four-stroke internal-combustion engines,
344 where, for single-cylinder engines, there is only one propulsive phase for two
345 revolutions of the crankshaft. A flywheel smooths the pulsatile impulses. Each
346 individual impulse is applied for about only 120° of crankshaft motion (28) to create
347 an angular impulse about the crankshaft. Multi-cylinder engines reduce the pulsatile
348 nature, so six-cylinder or greater configurations have no gaps in impulse. Race
349 engines that can exceed $18,000 \text{ rev}\cdot\text{min}^{-1}$ do not need a flywheel, because times
350 between impulses are miniscule.

351

352 The linear impulse in cycling or in engines creates a moment of force and hence
353 angular impulse. For convenience, performance in cycle ergometry or combustion
354 engines is expressed by *steady-state* power flows from the impulses that created them.

355 However, most human movement is dynamic, not steady state about a non-moving
356 axis of rotation; so, external power flow is a poor descriptor of performance compared
357 to the impulses that change velocity. For effective tangential forces in cycling,
358 coordination of recruitment of numerous muscles has to occur to optimise innervation,
359 elasticity of structures - principally muscle and tendon - muscle fibre types and
360 metabolic determinants of force production. This is vital both for sprinting and
361 prolonged cycling. As with four-stroke engines, each propulsive impulse occurs for
362 approximately 120° of crankshaft rotation. The mean torque (propulsive moment of
363 force) or mean power output are secondary expressions of the forces that have created
364 and modified the movement.

365

366 In running, the same logic applies. Running is a series of impulsive footstrikes with
367 the ground and, in endurance running, the athlete's structural, innervation, and
368 metabolic characteristics have to be optimised to maintain the ability to generate
369 impulse so as to maximise progression. This optimisation is an exceedingly complex
370 integration of biochemical, biomechanical, physiological, psychomotor, and other
371 factors (7). Endurance running needs to be economic so as to use as little chemical
372 energy as possible and similarly, minimise unproductive mechanical energy.

373

374 As Winter (30) clearly indicated, this optimization or economic production of
375 effective forces to modify movement should not to be confused with "efficiency".
376 Efficiency in engines is a ratio of the work output to the energy input. Efficiency
377 applied to human movement tries to create a simple ratio of the mechanical work
378 performed to the physiological energy expended:

379

380 $(\text{External mechanical work done/energy expended}) \times 100$

381

382 There are, however, numerous problems with this simple ratio as an indicator of
383 performance given the complexity both of the numerator and denominator. For
384 running, it is virtually impossible to meaningfully calculate the numerator in this
385 expression. So in turn, determination of a meaningful measure of efficiency is also
386 impossible (7, 30). There are also problems with uniquely separating the internal
387 mechanical energy (energy to move limbs) and the external mechanical energy. There
388 are special issues of journals on this topic for interested readers (2, 7). While is it also
389 tempting to assume the energy expended is simply the oxygen consumption measured
390 over the event, like the numerator there is clearly more chemical energy being used by
391 the body than is being accounted for in the denominator. Even so, misuse of
392 "efficiency" persists (11).

393

394 In field games, the ability to repeatedly accelerate, decelerate, change direction, and,
395 kick or strike a ball, determines effective performance. All of these actions require
396 the ability to repetitively generate well-timed and directed impulses. That ability
397 encompasses skill to perform the action per se and endurance to do so repeatedly.
398 Deficiencies in one or both will adversely affect performance.

399

400 For these activities, it is common to hear said or even read in research reports of
401 players performing supposedly at a "high work rate." If they were, by definition, their
402 power output would be high. However, the assessment of external mechanical work
403 done is not possible hence, the term "work rate" is inapplicable. It is colloquial and

404 should not be used (24). As the expression tends to be directed at players who run
405 large distances at high speeds, an acceptable alternative term is "high-intensity play".

406
407 In cycling, it might be convenient to assess external power output, but this construct is
408 an approximation of the fundamental requirement: external impulse generation by the
409 body. Moreover, selection of duration for mean power is important, since there are
410 considerable differences between mean and instantaneous power flows. In maximal-
411 intensity exercise, probably a mean value for at least a complete pedal revolution (32)
412 is required and in endurance activities, probably minutes if reliable values of this
413 secondary measure of performance are to be obtained.

414

415 9. **THE MISNOMER "CRITICAL POWER"**

416

417 In 1965, Monod and Scherrer (21) announced a laudable method to quantify an
418 intensity of exercise that marked a limit to what was tolerable, primarily through
419 aerobic metabolism, although it should be acknowledged that Hill (13) had outlined
420 the principle some 40 years earlier. This intensity was theoretical and represented
421 what could be sustained for infinite duration although in practice under laboratory
422 conditions, typical durations are 20 - 45 minutes (16). The intensity was termed
423 "critical power". A search on Medline (14 April 2015) revealed that, since Monod
424 and Scherrer's (21) founding publication, 208 exercise-based manuscripts have been
425 published that used the expression. At first sight, the term appears to be well
426 established, academically acceptable, and attractive but closer inspection quickly
427 reveals otherwise.

428

429 The majority of published studies (approximately two thirds) purporting to use
430 "critical power" have used some form of cycle-ergometer task. Typically, four to six
431 bouts of all-out cycling to volitional exhaustion are performed at different external
432 resistances. Ideally, each bout occurs on a separate day. There is a hyperbolic
433 relationship between on the ordinate, mean external power output measured on a
434 cycle ergometer (using the product of external resistance and flywheel rotation to
435 determine the distance travelled by an imaginary point on the periphery of the
436 flywheel) and on the abscissa, duration of exercise i.e. time to exhaustion. This
437 becomes a positive linear relationship when mean external power output is expressed
438 as a function of the reciprocal of duration. The vertical intercept of the relationship is
439 referred to as the "critical power". An alternative way to calculate "critical power" is
440 to determine external mechanical work done (J) i.e. power output multiplied by
441 duration, and relate that to duration. This too is a positive linear relationship. The
442 slope of the regression line has also been called "critical power".

443
444 However, changes in pedalling rate affect the identified "critical power"; it is less at
445 greater pedalling rates than at lower (4). This is explained principally by two factors.
446 First, Hill's (14) muscle force-velocity relationship and second, additional internal
447 mechanical work that is required to move the limbs (30). It is the latter that probably
448 has more effect and effectively highlights the folly of the term. The lower limbs are
449 substantial structures in that they comprise some 32% of total body mass (8). Forces
450 exerted by muscle to accelerate and decelerate these limbs sequester energy that
451 would otherwise be used for useful external output. Unless pedalling rates are
452 controlled, comparisons of "critical power" and the implied optimality of this concept
453 are compromised (4). According to Hill's force-velocity relationship in muscle (14),

454 the optimisation of power output requires different pedalling rates for different
455 external resistances. It is thus difficult to achieve overall optimisation of all factors
456 involved. Similar force-velocity and technique variables confound the use of external
457 power flow in jumping (20, 26). A scientist would ask, why abandon understanding
458 of 100% variance using impulse-momentum to use confounded secondary measures
459 such as power flows to study causative factors of movement?

460
461 Add to this the problems previously noted in the adequacy of external power as a
462 secondary measure of performance and the energy/work/power not accounted for, one
463 may conclude that exercise science literature should avoid use of the concept of
464 "critical power". Use of the term perpetuates the erroneous assumption that a vague,
465 colloquial meaning of "power" has a clear scientific meaning and is universally
466 applicable in the study of exercise performance. This parallels the problems for a
467 practitioner-understanding of muscular performance and exercise science when in the
468 strength and conditioning literature, the term "power" is used as a surrogate for all
469 muscular performance that includes extremes of force or speed (17).

470
471 When the concept is applied to running and swimming, performance can be expressed
472 as mean speed. Using similar mathematical principles as for cycling, there is a
473 positive linear relationship between distance to exhaustion on the ordinate and time to
474 exhaustion on the abscissa. The slope of the regression line gives "critical speed".
475 Clearly, the term "power" and hence "critical power" is inapplicable, although the
476 term was still used in 11 manuscripts. It should also be noted that the term "critical
477 velocity" is sometimes used (66 relevant Medline citations). Unfortunately, such use
478 is frequently incorrect. The vector nature of velocity challenges its use, whereas use

479 of the scalar “speed” is not so challenged. The scalar speed is preferable because it is
480 usually the measure of interest. Moreover, the term "speed" is more likely to be
481 understood by the athlete and his or her support team, whereas "power" could be
482 interpreted differently, as indicated earlier.

483
484 For isometric muscle activity, mean force can be plotted against duration of force
485 application. In this case, all the terms “work”, “power” and “speed” are inapplicable.
486 Monod and Scherrer (21) acknowledged this, albeit erroneously:

487
488 “Static contraction does not affect work in the physical sense.” (page 333)

489
490 The error is because “work” is simply inapplicable; it is the wrong mechanical
491 construct to use in this context.

492
493 Monod and Scherrer (21) were aware of this and in addition wrote:

494
495 “The critical rate of static work (sic) has the dimension of a force. Therefore it is in
496 fact a critical force.” (page 334).

497

498 10. **“CRITICAL INTENSITY”**

499

500 Despite its apparent popularity in the literature, the term “critical power” has limited
501 applicability. It should be restricted to: activities where steady-state mean external
502 power output is relevant to performance; when it can be meaningfully assessed; and
503 when confounding factors (e.g. pedalling rate) can be controlled. The potential

504 relevance of the term is also compromised by failure to consider the important
505 contributions of internal power requirements that are apparent in greater cycling rates
506 of the limbs. Instances where such assessment and control occur are rare in the
507 exercise science literature. The term “critical speed” can be used where it is
508 impossible, or at best exceptionally difficult, to get any measure of external power
509 output. The term “critical force” may be used where isometric muscle activity is the
510 interest because “power” is simply inapplicable.

511
512 However, “critical power”, “critical speed”, and “critical force” are all measures of
513 the same quality: a critical intensity of exercise. This intensity marks a limit to what is
514 sustainable before fatigue makes the performer slow down, or reduce force
515 application. It is inconsistent and nonsensical to have three names for the same
516 phenomenon. It is also incorrect to express critical power (a mechanical power) in the
517 units of speed ($\text{m}\cdot\text{s}^{-1}$), force (N), or torque ($\text{N}\cdot\text{m}$). Such expression is counter to
518 Newtonian mechanics, the SI, and standards of scientific reporting. Together, the
519 several terms and non-compliance with Newton are quite simply, not science. Monod
520 and Scherrer (21) identified this failing, but seemed unsure how to rectify matters.
521 Some 50 years on, the solution is remarkably simple: the term “critical power”
522 should be replaced with “critical intensity” and documented with the appropriate SI
523 units depending on the particular movement or action.

524
525 The ability to tolerate exercise at high intensity for long durations is the key
526 characteristic of successful endurance athletes. Importantly, this tolerance embraces
527 statics that is relevant to many activities and sports such as gymnastics, climbing,
528 cycling, swimming, and running.

529

530 11. **APPROPRIATENESS OF "INTENSITY"**

531 Use of "intensity" to express the challenge posed by exercise was first advocated by

532 Knuttgen (18). It is an elegant way to avoid misuse of mechanical constructs.

533 Objections to use of the term are unfounded. Intensity is in general use in the

534 categorisation of exercise into domains that are based on physiological responses.

535 Intensity domains are "moderate", "heavy", "very heavy" and "severe" (29) and

536 "extreme" (15). These categorisations apply to all forms of static and dynamic

537 exercise. The term is also used in the tripartite requirement for effective training i.e.

538 frequency, intensity and duration of training. Moreover, recent interest in high-

539 intensity interval training (10) further indicates support for acceptability and use of

540 the term.

541

542 The term "intensity" is recognised by the SI, but not defined universally. It is

543 expressed as $W \cdot m^{-2}$. However, a principal and established use of the term is in

544 luminescence to quantify brightness of light. The SI unit of luminous intensity is the

545 candela, i.e. power emitted by a light source in a particular direction. It has the unit

546 cd, roughly equivalent to the light emitted by a candle. However, the unit is not

547 expressed as $W \cdot m^{-2}$ although it could be considered to be traceable to the watt

548 because of its definition: the luminous intensity, in a given direction, of a source that

549 emits monochromatic radiation of a frequency 540×10^{12} hertz and that has a radiant550 intensity in that direction of $1/683$ watt per steradian. Moreover, another unit of light

551 is the lumen. This is a measure of luminous flux as opposed to radiant flux. The

552 former reflects the varying sensitivity of the human eye to different wavelengths of

553 light whereas the latter indicates power of all electromagnetic waves emitted,
554 independent of the eye's ability to perceive them. It is equivalent to $1 \text{ cd}\cdot\text{sr}^{-1}$.

555
556 While exercise could be perceived as a rate of movement through space i.e. $\text{W}\cdot\text{m}^{-2}$,
557 that would not permit application to isometric activity or the scalar speed. As science
558 develops in response to phenomena that emerge, either new units have to be
559 developed or old ones have to be adapted. The (Shorter) Oxford English Dictionary
560 defines intensity in physics as: "A (measurable) amount of energy, brightness,
561 magnetic field etc". The "etc." is important. The term "intensity" has a utility that
562 allows it to be applied to exercise. It avoids infatuation with "power" and other
563 constructs and provides a solution to correct what Monod and Scherrer themselves
564 acknowledged about "critical power": its inapplicability for isometric muscle activity
565 and where performance is expressed as the scalar speed (21). Added to which is
566 recognition that meaningful use of "power" is possible only if many pre-requirements
567 are satisfied. It is rare that such satisfaction occurs.

568

569 12. **CONCLUSION**

570 If sport and exercise science is to advance, it must uphold the principles and practices
571 of science. Descriptions of exercise must make correct use of basic scientific terms,
572 nomenclature, and units. Greater recognition and use of Newton's Second Law of
573 motion as the explanation of how forces modify movement, rather than less-accurate
574 secondary performance variables in research reports and their critical review, are
575 needed. Many errors in use of SI nomenclature can be rectified by adoption of the
576 term "intensity" to categorise exercise in terms of its actual or perceived challenge
577 and into domains based on physiological responses. While Monod and Scherrer's (21)

578 method to identify a limit of tolerance to exercise is a valuable way to investigate
579 mechanisms of fatigue, the self-acknowledged flaws in naming this limit “critical
580 power” are problematic. This problem can easily be rectified: the term should be re-
581 named “critical intensity” and performance documented by the SI units relevant to the
582 activity being studied. Universal adoption of intensity will help reduce the confusion
583 and perpetuation of erroneous understanding of mechanical work, energy, and power
584 in sport and exercise. Importantly, adoption of this recommendation by journal
585 editorial teams will help advance sport and exercise science.

586

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