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INVITED COMMENTARY

Standing on the Shoulders of Giants: Essential Papers in Sports and Exercise Physiology

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Purpose: The purpose of this survey was to create a list of essential historical and contemporary readings for undergraduate and graduate students in the field of exercise physiology. ***Methods:*** Fifty-two exercise physiologists/sport scientists served as referees, and each nominated ~25 papers for inclusion in the list. In total, 396 papers were nominated by the referees. This list was then sent back to the referees, with the instructions to nominate the "100 essential papers in sports and exercise physiology." ***Results:*** The referees cast 4722 votes. The 100 papers with the highest number of votes received 51% (2406) of the total number of votes. A total of 37 papers in the list of "100 essential papers" were published >50 years ago, and 63 papers were published since 1973. ***Conclusions:*** This list of essential studies will provide a perspective on contemporary studies, the "*giant's shoulders*" to enable young scholars to "see further" or to understand where they have "come from." This compilation is also meant to impress on students that, given the (lack of) technology available in the past, some of the early science required enormous intuitive leaps on the part of historical scientists.

Keywords: excercise science, heritage, historic development

The term "standing on the shoulders of giants" is a metaphor conveying that, in science, we make progress by building on previous discoveries. The concept dates from the 12th century, attributed to Bernard of Chartres, and is abundantly evident in the early history of science. It is most specifically remembered from a 1675 letter of Isaac Newton to Robert Hooke, "if I have seen further than others, it is by standing on the shoulders of giants." The expression is widely understood to mean that scientific knowledge is a *summation* of one's current work, applied to an existing body of knowledge, *even if part of that body of knowledge is no longer specifically correct*. From the standpoint of training young scholars, we have taken this to mean that the grounding of students depends upon them learning, understanding, and integrating the existing body of knowledge about any particular topic (eg, *what do we know, what do we need to know,* and following observation or experiment*, what do we now know).*

In early 2012, during the course of a walk around the lake in Langeraar (the Netherlands), we realized that our mutual experience was that many students were generally ill-prepared in terms of their understanding of the "deep history" in exercise physiology. While they seemed to do well with contemporary literature related to current research projects, indeed most journals were encouraging use of recent references, we found ourselves concerned that their understanding of less recent literature was deficient, in a way that made understanding the concept that the essence of scientific inquiry was the "self-correcting" nature of science, that scientific truth is transient, and that there will always be a better explanation for how things work. Accordingly, we asked ourselves whether we could come up with a list of *essential readings* to provide perspective to contemporary studies and, in so doing, provide the "giant's shoulders" that allows young scholars to "see further."

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Methods

As with all questions that one asks, there is an evolutionary process to reach an approach to answering questions. First, we derived a list of about a dozen folks with whom we were corresponding in our role as Editor(s) of the *International Journal of Sports Physiology and Performance* (*IJSPP*). We wrote to this group and asked them to nominate 10 to 20 papers that might fit into a list, nominally 100 papers, that would be essential for (graduate) students in exercise physiology to have read and be familiar with. We further asked them to particularly consider what might be considered "early papers" beginning in the time frame of the Nobel Prizes in Physiology or Medicine by August Krogh (1920) and AV Hill (1922; ~100 y ago), through 1973, and "contemporary" papers (post-1973). Our test group of "referees" returned an interesting list, with considerable overlap, suggesting to us that there was, indeed, the possibility of building a list of papers that might represent the "giant's shoulders." Alas, for all the promise of the concept, we had classes to teach, thesis projects to direct, and administrative work to do, and the *100 Essential Papers* project was put on the shelf, discussed frequently, but not completed.

In 2021, one of us retired from teaching, which created time to resume work on the project. After some discussion, we came up with an approach of asking a substantial number of "experts" for their opinion on what represented an essential paper. We chose this approach rather than relying on citation lists, as we felt that the informed opinion of our experts was more valuable than strictly quantitative measures. We created a list of 52 exercise physiology or sport scientists to serve as referees (including 6 past-presidents of the American College of Sports Medicine [ACSM], all 5 Editors of *IJSPP*, all current Associate Editors of *IJSPP*, 2 Editors of *Medicine and Science in Sports and Exercise* [*MSSE*], and 1 Editor of the *European Journal of Sport Science*). We repeated the early process, asking them to nominate ~25 papers for inclusion in the list, with at least 25% of the nominations coming from "early"

papers. Because of our unique history as Editors of *IJSPP* (C. Foster = 2010–2013, J.J. de Koning = 2018–2021), the list of referees is somewhat *IJSPP*-centric (sport-related applied physiology), although we intentionally included physiologists who had interests broader than the niche of *IJSPP*. We did our best to have a diverse list of referees relative to research specialty, geography, and gender. Any paper nominated, even 1 time, was included in the list of nominated papers. This list was then sent back to the referees, with the instructions to identify the "100 most essential papers," but not to attempt to rank order them, just include or exclude from the "100." This was done because we wanted to build a list that we thought students should read widely. We specifically did not want to identify a single "winning" paper, our goal was to create an educational tool, not have a contest where the "election might be stolen." Again, the referees were asked to select at least 25% of the papers from the "early" period. On the basis of the referees' votes, the papers were then categorized as being included or excluded from the list of "100 essential papers."

The referees who nominated papers and/or voted were: Barbara Ainsworth, James Anholm, Renato Barroso, Ralph Beneke, Daniel Bok, Daniel Boullosa, Martin Buchheit, Arturo Casado, Karim Chamari, Stephen Cheung, Cristina Cortis, Aaron Coutts, Hein Daanen, Brian Dawson, Larry Durstine, Marc Francaux, Bruce Gladden, Shona Halson, Thomas Haugen, Florentina Hettinga, Oliver Hue, Blair Johnson, Andrew Jones, Michael Joyner, Larry Kenney, Don Kirkendall, Rob Lamberts, Alejandro Lucia, Mike McGuigan, Romain Meeusen, Inigo Mujika, Kathy Myberg, Fabio Nakamura, Sophia Nimphius, Dionne Noordhof, Maria Francesca Piacentini, David Pyne, Bart Roelands, Øyvind Sandbakk, Stephen Seiler, James Skinner, Sabrina Skorski-Forster, Alan St Clair Gibson, Trent Stellingwerff, Oscar Suman, Espen Tønnesson, Christian Thiel, Alex Urhausen, Lutz Vogt, and Randy Wilber. We thank them, particularly as the process took longer than we had expected.

Results

From the combined 2012 and 2022 surveys, 396 papers were nominated by the experts. From these nominated papers, 298 were published after 1973. The list of nominated papers can be found in the Supplementary Material (available online). We chose to cut off the list in 2018, first because 1923, 1973, and 2018 are more or less 50-year segments and second because it is hard to evaluate the long-term value of more recent papers and 5 years (2018–2023) seemed to be a reasonable cut point.

The referees cast 4722 votes. The 100 papers with the highest number of votes received 51% (2406) of the total number of votes. A total of 37 papers in the list of "100 essential papers" were published >50 years ago. The "100 essential papers" are presented below. It is important to understand, however, that there were ~200 papers which "could have" made the list. Indeed, the biggest discussions and arguments that we had were whether to make a bigger list (ultimately, we decided to list only 100) or to include some of what we thought were real classics (beyond the votes of the referees) that did not get the votes, or to list only one of several vote getting papers that told the same story. Inevitably, as the makers of the list, we were overnominated and overvoted, which we did try to correct. Also, with very few exceptions, the list includes too little about health and exercise or about clinical physiology, the votes were *IJSPP* centric, as was our selection of referees. In the end, the list is *our* best list, love it or hate it, it is *ours*. We hope you and your students find it useful.

100 Essential Papers

The purpose of our survey was to create "giant's shoulders" for (graduate) students to "stand on," as they familiarize themselves with the field of sports and exercise physiology. The availability of scientific literature is immense and accelerating. Navigating this information is difficult, even with the availability of sophisticated search engines. This list, drawn up with the help of our "referees," can give a head start in mastering the field. It was our intention to include a certain percentage of older manuscripts. Many of the older manuscripts selected laid the foundations for theories and concepts that are still relevant today (eg, lactate metabolism). Understandings have changed, often with the help of better technology and research methods, but a deeper understanding is advanced when the work of the originators of a concept is known. From our perspective, science is an evolutionary process and the search for the ultimate truth continues indefinitely, as science is self-correcting.

The list of "100" has a number of limitations. First, the list of 100 essential papers would have looked different if 50 different experts (and 2 different authors) had been involved in the nomination and voting process. The experts were mainly centered around *IJSPP*, which resulted in a bias toward sports physiology and performance. We encourage similar surveys in other areas of sport science to help students navigate the literature. In very "mature" journals such as *Journal of Applied Physiology* or *MSSE*, it might even be possible to make a list of 100 essential papers from a single journal. Second, the selection process was not based on a scientific analysis of bibliometric data, which resulted in some well-cited authors not being included in the list. This should not be seen as a disqualification, but rather as an effect of the bias discussed above. Third, the expert panel was asked to nominate papers published since Krogh (1920) and Hill (1922) were awarded the Nobel Prize. We recognize that important discoveries were made before the 20th century, this event was just a convenient landmark for us. Last, the nomination process took place over a period of 10 years. All the nominations were made in 2012 or 2022 and the votes in 2022, so this is not expected to have any effect on the scoring.

Rather than provide a historical chronology of the field of sports and exercise physiology, we have chosen to group the 100 papers into a number of subcategories: muscle physiology,[1–5] muscular energetics/metabolism,[6–20] aerobic work/VO_2max,[21–37] anaerobic work,[38–42] fatigue/perception of effort,[43–47] endurance training,[48–58] resistance training,[59–61] high-intensity training,[62,63] altitude,[64–67] monitoring training/overtraining,[68–72] periodization/tapering,[73–75] thermophysiology,[76,77] performance,[78–96] and physical activity and health.[97–100]

Practical Application and Conclusions

This list of 100 essential readings will provide a perspective on contemporary studies and the "giant's shoulders" to enable young scholars to "see further," or to understand where they have "come from." Also, it is intended to help young scholars recognize that there is very little "bad science," it is just that more contemporary science has "self-corrected" by virtue of either better observations (technology) or better experimental designs, data analysis, and/or interpretations. It is also meant to impress on students that, given the (lack of) technology available in the past, some of the early science required enormous intuitive leaps on the part of historical scientists. That is why these folks (Krogh, Hill, Dill, di Prampero, Margaria, Robinson, Astrand, Saltin, etc) have such enormous

reputations. They did something fundamentally good and created "shoulders" for all of us to stand on.

Acknowledgment

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100 Essential Papers in Sport and Exercise Physiology

Muscle Physiology

1. Krogh A. The number and distribution of capillaries in muscles with calculations of the oxygen pressure head necessary for supplying the tissue. *J Physiol*. 1919;52(6):409–415. doi:10.1113/jphysiol.1919.sp001839
2. Hill AV. The mechanism of muscular contraction. *Physiol Rev*. 1922;2(2):310–341. doi:10.1152/physrev.1922.2.2.310
3. Huxley AF, Niedergerke R. Structural changes in muscle during contraction; interference microscopy of living muscle fibres. *Nature*. 1954;173(4412):971–973. doi:10.1038/173971a0
4. Costill DL, Fink WJ, Pollock ML. Muscle fiber composition and enzyme activities of elite distance runners. *Med Sci Sports*. 1976;8(2):96–100.
5. Thorstensson A, Karlsson J. Fatiguability and fibre composition of human skeletal muscle. *Acta Physiol Scand*. 1976;98(3):318–322. doi:10.1111/j.1748-1716.1976.tb10316.x

Muscular Energetics/Metabolism

6. Krogh A, Lindhard J. The relative value of fat and carbohydrate as sources of muscular energy: with appendices on the correlation between standard metabolism and the respiratory quotient during rest and work. *Biochem J*. 1920;14(3–4):290–363. doi:10.1042/bj0140290
7. Hill AV, Lupton H. Muscular exercise, lactic acid, and the supply and utilization of oxygen. *Quart J Med*. 1923;16(62):135–171. doi:10.1093/qjmed/os-16.62.135
8. Dill DB, Edwards HT, Talbott JH. Studies in muscular activity: VII. factors limiting the capacity for work. *J Physiol*. 1932;77(1):49–62. doi:10.1113/jphysiol.1932.sp002949
9. Margaria R, Edwards HT, Dill DB. The possible mechanisms of contracting and paying the oxygen debt and the role of lactic acid in muscular contraction. *Am J Physiol*. 1933;106(3):689–715. doi:10.1152/ajplegacy.1933.106.3.689
10. Bergström J, Hultman E. Muscle glycogen synthesis after exercise: an enhancing factor localized to the muscle cells in man. *Nature*. 1966;210(5033):309–310. doi:10.1038/210309a0
11. Bergström J, Hermansen L, Hultman E, Saltin B. Diet, muscle glycogen and physical performance. *Acta Physiol Scand*. 1967;71(2):140–150. doi:10.1111/j.1748-1716.1967.tb03720.x
12. Hermansen L, Hultman E, Saltin B. Muscle glycogen during prolonged severe exercise. *Acta Physiol Scand*. 1967;71(2):129–139. doi:10.1111/j.1748-1716.1967.tb03719.x
13. Karlsson J, Saltin B. Lactate, ATP, and CP in working muscles during exhaustive exercise in man. *J Appl Physiol*. 1970;29(5):596–602. doi:10.1152/jappl.1970.29.5.598
14. Krebs HA. The history of the tricarboxylic acid cycle. *Perspect Biol Med*. 1970;14(1):154–170. doi:10.1353/pbm.1970.0001
15. Karlsson J, Saltin B. Diet, muscle glycogen, and endurance performance. *J Appl Physiol*. 1971;31(2):203–206. doi:10.1152/jappl.1971.31.2.203
16. Saltin B. Metabolic fundamentals in exercise. *Med Sci Sports*. 1973;5(3):137–146.
17. Essén B, Jansson E, Henriksson J, Taylor AW, Saltin B. Metabolic characteristics of fibre types in human skeletal muscle. *Acta Physiol Scand*. 1975;95(2):153–165. doi:10.1111/j.1748-1716.1975.tb10038.x
18. di Prampero PE. Energetics of muscular exercise. *Rev Physiol Biochem Pharmacol*. 1981;89:143–222. doi:10.1007/BFb0035266
19. Gladden LB. 200th anniversary of lactate research in muscle. *Exerc Sport Sci Rev*. 2008;36(3):109–115. doi:10.1097/JES.0b013e31817c0038
20. Jones AM, Wilkerson DP, DiMenna F, Fulford J, Poole DC. Muscle metabolic responses to exercise above and below the "critical power" assessed using 31P-MRS. *Am J Physiol Regul Integr Comp Physiol*. 2008;294(2):R585–R593. doi:10.1152/ajpregu.00731.2007

Aerobic Work/VO_2max

21. Taylor HL, Buskirk E, Henschel A. Maximal oxygen intake as an objective measure of cardio-respiratory performance. *J Appl Physiol*. 1955;8(1):73–80. doi:10.1152/jappl.1955.8.1.73
22. Mitchell JH, Sproule BJ, Chapman CB. The physiological meaning of the maximal oxygen intake test. *J Clin Invest*. 1958;37(4):538–547. doi:10.1172/JCI103636
23. Astrand PO, Saltin B. Maximal oxygen uptake and heart rate in various types of muscular activity. *J Appl Physiol*. 1961;16:977–981. doi:10.1152/jappl.1961.16.6.977
24. Astrand PO, Cuddy TE, Saltin B, Stenberg J. Cardiac output during submaximal and maximal work. *J Appl Physiol*. 1964;19:268–274. doi:10.1152/jappl.1964.19.2.268
25. Saltin B, Stenberg J. Circulatory response to prolonged severe exercise. *J Appl Physiol*. 1964;19:833–838. doi:10.1152/jappl.1964.19.5.833
26. Holloszy JO. Biochemical adaptations in muscle. Effects of exercise on mitochondrial oxygen uptake and respiratory enzyme activity in skeletal muscle. *J Biol Chem*. 1967;242(9):2278–2282.
27. Saltin B, Astrand PO. Maximal oxygen uptake in athletes. *J Appl Physiol*. 1967;23(3):353–358. doi:10.1152/jappl.1967.23.3.353
28. Costill DL, Bowers R, Branam G, Sparks K. Muscle glycogen utilization during prolonged exercise on successive days. *J Appl Physiol*. 1971;31(6):834–838. doi:10.1152/jappl.1971.31.6.834
29. Whipp BJ, Wasserman K. Oxygen uptake kinetics for various intensities of constant-load work. *J Appl Physiol*. 1972;33(3):351–356. doi:10.1152/jappl.1972.33.3.351
30. Costill DL, Thomason H, Roberts E. Fractional utilization of the aerobic capacity during distance running. *Med Sci Sports*. 1973;5(4):248–252.
31. Wasserman K, Whipp BJ, Koyl SN, Beaver WL. Anaerobic threshold and respiratory gas exchange during exercise. *J Appl Physiol*. 1973;35(2):236–243. doi:10.1152/jappl.1973.35.2.236
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33. Howley ET, Bassett DR, Welch HG. Criteria for maximal oxygen uptake: review and commentary. *Med Sci Sports Exerc*. 1995;27(9):1292–1301.
34. Dempsey JA, Wagner PD. Exercise-induced arterial hypoxemia. *J Appl Physiol Bethesda Md 1985*. 1999;87(6):1997–2006. doi:10.1152/jappl.1999.87.6.1997
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Anaerobic Work

38. Komi PV, Rusko H, Vos J, Vihko V. Anaerobic performance capacity in athletes. *Acta Physiol Scand*. 1977;100(1):107–114. doi:10.1111/j.1748-1716.1977.tb05926.x
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Fatigue/Perception of Effort

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Endurance Training

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Resistance Training

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High-Intensity Training

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Altitude

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Monitoring Training/Overtraining

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Periodization/Tapering

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Thermophysiology

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Performance

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