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The Evolution of World-Class Endurance Training: The Scientist's View on Current and Future Trends

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Abstract

81

82 **Background:** Elite sport is continuously evolving. World records keep falling and athletes
83 from a longer list of countries are involved. **Purpose:** This commentary was designed to
84 provide insights into present and future trends associated with world-class endurance training
85 based on the perspectives, experience, and knowledge of an expert panel of 25 applied sports
86 scientists. **Results:** The key drivers of development observed in the past 10-15 years were
87 related to 1) more accessible scientific knowledge for coaches and athletes, combined with 2)
88 better integration of practical and scientific exchange across multidisciplinary perspectives
89 within professionalized elite athlete support structures, as well as 3) utilization of new
90 technological advances. Based on these perspectives, we discerned and exemplified the main
91 trends in the practice of endurance sports into the following categories: better understanding of
92 sport-specific demands; improved competition execution; larger, more specific, and precise
93 training loads; improved training quality; and a professionalized and healthier lifestyle. The
94 main areas expected to drive future improvements were associated with more extensive use of
95 advanced technology for monitoring and prescribing training and recovery, more precise use
96 of environmental and nutritional interventions, better understanding of athlete-equipment
97 interactions, and greater emphasis on preventing injuries and illnesses. **Conclusions:** These
98 expert insights can serve as a platform and inspiration to develop new hypotheses and ideas,
99 encourage future collaboration between researchers and sport practitioners and, perhaps most
100 importantly, stimulate curiosity and further collaborative studies about the training,
101 physiology, and performance of endurance athletes.

102

103 **Key words:** athlete health, endurance performance, sports technology, training intensity,
104 training load, training quality.

105 **Introduction**

106

107 Elite sport is continuously evolving, as illustrated by world records being broken and the
108 involvement of a greater diversity of countries and athletes, driving improvements in athletic
109 performance. Explanations for this continued performance evolution are multifaceted, and
110 likely include the optimization of athlete training and competitive periodization, as well as
111 recent advancements in technologies, equipment, and scientific knowledge, all accessible to
112 larger audiences. However, research on elite athletes is often constrained by underlying
113 challenges, such as interruptions to coaching and training programs, as well as limitations in
114 the type, quality or applicability of research studies that can be executed with elite performers.
115 To gain complementary insight into current and future trends associated with world-class
116 endurance training, this commentary is based on the perspectives, experience, and knowledge
117 of an expert panel of applied sports scientists.

118

119 **Methods**

120 To capture key insights about the evolution of endurance training and performance, we solicited
121 and aggregated expert judgements through a structured elicitation protocol. In the first step,
122 two questions were posed by the first and last author to an expert panel of 25 acknowledged
123 sport scientists (5 women and 20 men) with experiences of working closely with world-leading
124 endurance athletes and coaches over the last decade(s). Collectively, this multinational panel
125 had multidisciplinary (i.e., exercise physiology, biomechanics, sports analytics, nutrition, and
126 sports medicine) experience of working with male and female athletes from 15 different nations
127 and representing all Olympic endurance sports.

128

129 The two questions were: (1) *What are the most important trends related directly or indirectly*
130 *to the training and improved performance of the world's best endurance athletes during the*
131 *past 10-15 years?* and (2) *Which advances will contribute to further improving endurance*
132 *performance during the next 10-15 years?* To allow diversity of opinion, all scientists were
133 asked to prioritize three key points for each question individually, and to explain and exemplify
134 their choices. Consent was given on the basis that replies could be used for the purpose of this
135 commentary.

136

137 In the next steps, all responses were aggregated into initial thematic categories by the first and
138 last author. Iterative refinement was undertaken by facilitated negotiation and discussion over
139 e-mail among all authors, until final consensus on main categories, as well as representative
140 examples and explanations was reached.

141

142

143 **Recent and Contemporary Trends in Endurance Training**

144 To address recent and contemporary trends, the answers to the first question were categorized
145 into two dimensions: the underlying mechanisms driving the development (*the why*), and the
146 effects of these factors on sport practices (*the what*).

147

148 A main driver of development in endurance training methods was more relevant scientific
149 knowledge accessible to coaches and athletes, combined with better integration and exchange
150 of practical and scientific knowledge. In this context, easier access to scientific and
151 experienced-based knowledge through open-access journals, media (e.g., popular science
152 articles, podcasts, Twitter, Instagram, YouTube, etc.) and various other communication
153 channels (e.g., conferences/summits, webinars, workshops, personal conversations, etc.) has
154 facilitated faster and wider learning and possibly more effective implementation into sport
155 practice. Two potential challenges associated with effective utilization of publicly-available
156 information are 1) the ability to filter useful versus less useful content, and 2) translation of this
157 specific information into a holistic training process. This translation process will require close
158 collaboration between athletes, coaches, and various domain experts.

159
160 Another main driver was the implementation of technological advances, with better equipment
161 and more validated tools/wearables for monitoring and analyzing training, performance, and
162 recovery. The sports science laboratory has moved out to the roads, tracks, pools, lakes, trails,
163 rivers, and mountains, where endurance athletes train daily. A critical challenge in this context
164 is to assure that the continuously collected data stream is as reliable and valid as possible.

165
166 Elite athlete health and performance support structures are now often organized in
167 multidisciplinary centers or teams. This was regarded as a complementary factor facilitating
168 effective implementation of the extended knowledge and new technological solutions into the
169 holistic training, competition, and performance process. High-performance sports directors (or
170 equivalent) and coaches are, in general, now more well-educated in coaching and/or sports
171 science. In addition, they are more open to the potential benefits of multi- and intradisciplinary
172 collaboration among athletes, coaches, scientists, and other experts.

173
174 Based on these driving factors, we discerned 5 important trends in the practice of endurance
175 sports that have evolved over the last 10-15 years.

176

177 *1) Better understanding of sport-specific demands*

178

179 A more interdisciplinary and integrated understanding of physiological, technical, tactical,
180 nutritional, and mental aspects underlying performance, on the basis of optimal mental and
181 physical health, has evolved in sports.¹ For example, different exercise modes can elicit highly
182 distinct metabolic, mechanical, and muscular loading, which can have significant
183 consequences for training and recovery processes.² In this context, the technological possibility
184 to measure performance, training load, and recovery under ecologically valid conditions, in
185 combination with advanced performance modelling, has extended our understanding beyond
186 the traditional performance-determining factors.³ Examples of complementary concepts are the
187 impact of resilience/durability during long-duration exercise,⁴ or the implementation of various
188 models describing aerobic and anaerobic kinetics during intermittent exercise. A better
189 understanding of nutritional strategies has also played a significant role both for optimizing
190 performance, and sustainable tolerance and execution of high daily training loads. This may

191 include optimal carbohydrate (CHO) intake (daily and during training and competition)⁵ and
192 associated nutritional periodization to meet the demands of the sport.⁶⁷

193

194 2) *Improved competition execution*

195

196 More accurate technological measures of performance and advanced performance models have
197 improved pacing strategies,⁸ as well as the ability of each athlete (and their coaches) to identify
198 and focus on his/her own individual strengths and weaknesses. Examples of this are the
199 extensive use of various wearable devices, such as power meters, global positioning/navigation
200 satellite systems (GPS/GNSS), and inertial movement units (IMUs) in many sports.^{9, 10} With
201 the combination of machine learning and domain competence, these developments have
202 provided new insights in many sports, although the practical and ethical challenges of
203 accumulating and processing large sets of personal data should also be acknowledged.

204

205 Without doubt, improved equipment has been vital for performance development in many
206 endurance sports, with the clap skate in speed skating,¹¹ carbon fibre use in cycling, rowing,
207 kayak and paralympic events, and “super-shoes” in running¹² being primary examples. Another
208 factor is improved preparation strategies for competitions held in different environmental
209 conditions such as altitude and the heat.¹³ Furthermore, sport-specific and individualized
210 nutritional intake during competitions (e.g., CHO intake and the use of various ergogenic aids)^{5,}
211 ¹⁴⁻¹⁶ was highlighted by many of the respondents.

212

213 3) *Larger, more specific, and precise training loads*

214

215 Many of the scientists in the expert panel highlighted that world-leading endurance athletes
216 now perform and tolerate higher training volumes than previously recorded. However, others
217 had observed more precise and calculated training models, allowing a higher volume or density
218 of competition-specific training. In both cases, the detection of individualized “sweet-spots”
219 with respect to training volume and intensity, as well as individualized training intensity
220 distribution and more detailed monitoring and analysis of capacity developments, were
221 highlighted as success criteria. One of the trends observed by many of the scientists was more
222 of the intense training being performed in a “controlled zone”, thereby allowing higher volume
223 and/or frequency of sessions at competition-relevant speeds.¹⁷ However, the specific changes
224 in training patterns, as well as the underlying mechanisms, need to be verified for different
225 endurance sports.

226

227 The following aspects were highlighted as the main facilitators for athletes accumulating higher
228 training volumes or competition-specific loads: shorter transition/recovery periods between the
229 competition period and the following macrocycle, higher training loads both early in the
230 training year and during the competition period, and more conscious periodization and load-
231 recovery monitoring. Other key factors allowing more precise training loads included improved
232 training facilities (e.g., better roller-ski tracks for cross-country skiers and biathletes, and more
233 indoor tracks in cycling, athletics and speed skating), and improved equipment. In addition,
234 more advanced injury prevention measures seem to provide better continuity of training.^{18, 19}

235

236 More women worldwide now have the possibility to train and compete professionally in
237 endurance sports, with a higher status of female competitions, more financial support, and
238 better coaching available to female athletes. In addition, many sporting environments now
239 possess greater awareness of and willingness to communicate about aspects of female
240 physiology and health (e.g., the influence of the menstrual cycle,^{20, 21} hormonal
241 contraception,²² and pregnancy/post-partum²³⁻²⁶), and their potential impact on training and
242 performance. With the increase in professional opportunities for female athletes, and an
243 improved understanding of the specific challenges facing women in elite sport, larger, more
244 specific, and/or precise training loads are particularly observed in female athletes.

245

246 Finally, several respondents highlighted that more systematic inclusion of environmental
247 stressors, such as altitude²⁷ and heat¹³, periodized in the training process has become more
248 common, particularly when preparing for events held under challenging climatic conditions.

249

250 4) *Improved training quality*

251

252 Factors associated with improved training quality²⁸ were highlighted by many of the
253 respondents. This list included both the quality of the holistic training process, performed in
254 close cooperation between athletes, coaches and multidisciplinary support teams, as well as
255 better planning, execution, and debriefing routines of single training sessions. One key factor
256 for the latter dimension was more precise and disciplined intensity control, facilitated by
257 greater awareness of how the variables of exercise prescription influence training tolerance and
258 load, as well as better technologies to monitor these features in various conditions. Another
259 example was use of better equipment in training, such as “super shoes” with new-age foams
260 that allow for better cushioning and recovery, thereby facilitating more training at high speeds.
261 Such developments may also contribute to narrowing the gap between training prescription and
262 execution.

263

264 Improved training quality was also associated with more individualized training in terms of
265 load prescription, micro-periodization, and daily session programming. For example,
266 implementation of strength and power training based on individual profiling in relation to the
267 physiological and technical requirements of each sport is now much more advanced in sport
268 practice. Such individual profiling, in combination with systematic monitoring of training and
269 testing, provides important objective information concerning how training is executed and the
270 corresponding adaptations. In addition, the role of the coach and multidisciplinary support staff
271 in using such information to prepare and debrief the athlete systematically, as well as how the
272 support staff work synergistically with coaches and athletes,²⁹ were also highlighted as having
273 a positive influence on training quality and performance.

274

275 5) *A more professional and healthier lifestyle*

276

277 Employing a more holistic approach to athlete development, by understanding and considering
278 all factors influencing their lives, has benefited both individual and team-sport athletes.³⁰

279 Greater professionalization of many sports has enabled athletes to pursue a full-time athletic
280 career, which can create a healthier lifestyle through enhanced recovery. More knowledge and
281 greater awareness of injury prevention and health management strategies are argued as
282 important for facilitating the continuity and sustainability of training, as well as prolonging the
283 careers of elite athletes.¹⁸ For example, greater knowledge and awareness of the importance of
284 energy availability, periodized and individualized nutrition, and sleep have contributed to
285 improved recovery.³¹ The same paradigm applies to the inclusion of systematic monitoring of
286 recovery parameters such as resting heart rate, heart rate variability, and sleep metrics as part
287 of the monitoring systems. In addition, greater focus on the mental health of athletes³² and
288 coaches³³ was regarded as imperative.

289

290 **Future Trends in Endurance Training**

291

292 The expert panel generally expected the factors underpinning improved endurance training and
293 performance to continue to evolve in the upcoming 10-15 years. However, some perennial
294 aspects of endurance training received particular attention, and a few new aspects were
295 highlighted as key areas for improvement in the future.

296

297 First, more extensive and reliable use of advanced technology for evidence-based monitoring
298 of training, recovery, and performance is expected. Importantly, these technologies and the
299 insights they provide must be combined in a holistic, sport-specific, and integrated fashion with
300 the individual athlete's own developmental needs. This approach will likely allow more
301 effective individualization of training. In this context, artificial intelligence (AI) and its
302 associated opportunities are evolving very quickly and may permit individualized prescription
303 of training; for example, when combined with innovative, non-invasive technologies assessing
304 muscle fibre types and other important individual physiological characteristics. As part of this
305 process, more detailed knowledge about how to precisely use combinations of training loads,
306 environmental stressors and nutritional interventions to optimize physiological adaptations and
307 performance is expected. Furthermore, a more advanced understanding of athlete-equipment
308 interactions leading to greater tolerance of sport-specific training and improved performance
309 is also suggested as a future trend.

310

311 A greater emphasis on the prevention of health problems³⁴ will allow more athletes to train
312 with continuity over longer durations and this is clearly an area with further possibilities for
313 improvement. A greater focus on female athletes also creates opportunities for future
314 improvement,³⁵ especially given the historical lack of knowledge and support that has likely
315 limited performance development and career longevity in this population. Programs designed
316 to prevent injuries, illnesses, Relative Energy Deficiency in Sport (REDs) and/or eating
317 disorders and other unhealthy behaviours need to be customized, fine-tuned and implemented
318 broadly. Aspects relating to the preservation of mental health are also expected to receive more
319 attention over the coming years. Overall, a more comprehensive approach to optimizing and
320 maintaining good athlete health should permit more athletes to attain their full potential.

321

322 Finally, the continuous development and adjustment of sport science curriculums within
323 universities and federations in many countries will translate to improved scientific knowledge
324 among coaches, athletes, and practitioners, facilitating greater transfer of knowledge within
325 and between multidisciplinary teams.

326

327 **Practical Applications and Conclusions**

328

329 From the perspective of an expert panel of 25 applied sport scientists, this commentary has
330 facilitated the sharing of ideas, experience and knowledge between individuals involved in a
331 variety of endurance sports, research areas, and athletic communities. These insights are
332 summarized in Table 1 and can serve as a platform and inspiration for developing new
333 hypotheses, encourage future collaboration between researchers and sport practitioners and,
334 perhaps most importantly, stimulate curiosity and fruitful collaborative studies about the
335 training, physiology, health, and performance of endurance athletes. It would be highly
336 enlightening to pose these same questions to elite-level athletes, coaches and support staff
337 within different sports and nations. Although most of the content in this commentary should be
338 relevant both for Olympic and Paralympic endurance sports, the evolution of para-specific
339 aspects should be further explored in upcoming studies.

340

341

Include Table 1 around here

342

343

344 **Conflicts of interest statement**

345 The first author of this commentary is the Editor-in-Chief of the *International Journal of Sports*
346 *Physiology and Performance*, and several of the authors are associate editors or editorial board
347 members in the journal. Paul Laursen is co-founder of HIIT Science Inc and Athletica Inc. The
348 possibility of publication-bias was discussed critically and evaluated among editors, and none
349 of the authors, including those with editorial roles, had the opportunity to influence the
350 independent review process.

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Table 1. Summary of the present and future trends associated with world-class endurance training based on the perspectives, experience, and knowledge of an expert panel of 25 applied sports scientists.

Key drivers of development observed in the past 10-15 years	Main trends in the practice of endurance sports in the past 10-15 years	The main areas expected to drive future improvements
<ul style="list-style-type: none"> • More accessible scientific knowledge for coaches and athletes • Better integration of practical and scientific exchange across multidisciplinary perspectives within professionalized elite athlete support structures • Utilization of new technological advances 	<ul style="list-style-type: none"> • Better understanding of sport-specific demands • Improved competition execution • Larger, more specific, and precise training loads • Improved training quality • A professionalized and healthier lifestyle 	<ul style="list-style-type: none"> • More extensive use of advanced technology for monitoring and prescribing training and recovery • More precise use of heat and altitude interventions, and nutritional interventions • Better understanding of athlete-equipment interactions • Greater emphasis on preventing injuries and illnesses