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Current insights in the age-related decline in sports performance of the older athlete

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Abstract:	The higher performance level of master athletes compared to non-athletes is often associated with better health throughout life. However, even the physical performance of master athletes declines with age, and this decline accelerates from about the age of 70 years onwards. A progressive loss of muscle mass, declines in force and power generating capacity, decreased flexibility and the concomitant decline in specific tension characterize the muscular changes underlying performance declines. In the cardiovascular system, declines in stroke volume and cardiac output, and cardiac and vascular stiffness contribute to a decreasing performance. Recent studies have shown that long-term endurance exercise in master athletes does not only have positive effects, but is associated with an increased incidence of atrial fibrillation, atherosclerotic plaques and aortic dilation, and even more so in men than in women. Recently, larger longitudinal datasets were analysed and showed that the age-related decline in performance was similar in longitudinal and cross-sectional data. In conclusion, regular physical activity enhances the exercise capacity, and hence quality of life in old age, but it is not without risks.

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Abstract

The higher performance level of master athletes compared to non-athletes is often associated with better health throughout life. However, even the physical performance of master athletes declines with age, and this decline accelerates from about the age of 70 years onwards. A progressive loss of muscle mass, declines in force and power generating capacity, decreased flexibility and the concomitant decline in specific tension characterize the muscular changes underlying performance declines. In the cardiovascular system, declines in stroke volume and cardiac output, and cardiac and vascular stiffness contribute to a decreasing performance. Recent studies have shown that long-term endurance exercise in master athletes does not only have positive effects, but is associated with an increased incidence of atrial fibrillation, atherosclerotic plaques and aortic dilation, and even more so in men than in women. Recently, larger longitudinal datasets were analysed and showed that the age-related decline in performance was similar in longitudinal and cross-sectional data. In conclusion, regular physical activity enhances the exercise capacity, and hence quality of life in old age, but it is not without risks.

Keywords: longevity, active ageing, running, muscle, cardiovascular, longitudinal, cross-sectional, athletics

Introduction

In an ageing society, performance losses with age caused by a progressive decline in the reserve of organ functions affect the everyday lives of many. Mobility limitations connected to frailty and sarcopenia are often associated with a reduced quality of life [1]. A sedentary lifestyle contributes to a number of chronic diseases across physiological systems [2], such as the metabolic syndrome, diabetes, cardiovascular conditions and even cancer, that all have a significant detrimental impact on the quality of life in old age [3].

While the life expectancy in the Western world has increased, this has not been accompanied by a proportional increase in the healthy life expectancy, which led to a drive to extend the years of a good quality of life, or "Healthy ageing" [4]. A number of anti-ageing interventions, including pharmaceuticals, calorie restriction, and genetic alterations (in model organisms), are known to mitigate the ageing process, primarily via tackling cellular senescence [5,6] and extend longevity [7].

One factor that is associated with a better general fitness and cognitive function, and is suggested to flatten the physical performance decline curve is regular physical activity [8,9,10]. This physical activity does not necessarily need to be a competitive sport. For example, a lower risk of frailty may already be achieved by regular physical activity due to pet ownership [11]. However, to assess the benefits of regular physical activity, competing athletes are often studied as their performance is standardized in comparable settings and probably reflects the close-to-maximal achievable performance at a given age. This is particularly true for sports where results are measured in objective metrics, such as times and distances, as occurs in the track and field disciplines, swimming, rowing, cycling, Nordic skiing, weight lifting, long-distance running and triathlon events [12-19], and other master sports, such as tennis and judo [20,21].

Master athletes compete in 5-year bands from the age of 35 years, often into their 80s or even 90s and possess substantially better anthropometric, physical function and general health characteristics than even active age-matched peers [22]. In recent years, online results and rankings databases have increased in numbers and size, and some of them provide longitudinal data of many individual athletes, such as the Swedish [14] and Canadian [23] master athletics databases. Despite the fact that cross-sectional data often show a lower performance at any age than longitudinal data, they are usually easier to obtain

[10,14,24]. In the past few years, however, several groups have managed to analyse and publish larger longitudinal datasets covering a greater number of individual years. This review discusses recent papers dealing with longitudinal performance trends, and new findings in changes in skeletal muscle and the cardiovascular and respiratory system in older athletes.

Age-related performance declines in sports

Despite the fact that physical performance decline trajectories are not linear, but usually best described with second-order polynomials (**Figure 1**), linear regression models are often applied to enable comparisons of the rate of decline in different sports [14,24]. **Table 1** shows percent decline rates in several sports for both sexes and indicates that in general the decline rate increases with increasing age in all disciplines.

Acceleration of the age-related rate of performance decline

In a cross-sectional dataset with more than 27,000 results an accelerated decline in performance after the age of 70 years in throwing and other track and field disciplines was observed [15,25], something reported in many other cross-sectional studies [25,26,27,28]. Also, in longitudinal studies, an accelerated rate of decline beyond the age of 70 years has been found. For instance, in a longitudinal dataset from Sweden with more than 83,000 results for 16 track and field disciplines, the rates of performance decline after the age of 70 were 1.7 times (men) and 1.4 times (women) as steep as before [14], and this rate of decline may accelerate even further in older age [14,27]. Such a progressively accelerating performance decline beyond the age of 70 years is not limited to track and field athletics, but has also been observed in swimming, where the performance of 321 women and 319 men showed a faster decline after the age of 70 years in a 12-year follow up study [26]. Even within individual athletes, a progressively increasing rate in performance decline can be seen. For instance, a male master athlete who participated in running disciplines varying from 1500 m to marathon, exhibited a progressively increasing rate of decline, particularly after the age of 80 years, despite a continuous extensive exercise volume [29] and a similar observation was reported in a 97-year-old master athlete with results in several disciplines [30]. One possible cause of this accelerated decline in performance is the increased rate of decline of muscle mass that occurs after around the age of 70 years [31].

In swimmers, the percentage decline rate was larger in long-duration than short-duration events, and greater in women than in men in the short-duration disciplines [26]. Sousa et al. [19] showed in two master ultra-triathletes between 33-51 and 40-61 years of age that running was the discipline with the greatest performance-decline rate for both athletes, compared to cycling and swimming. While these observations suggest that the rate of performance decline differs between disciplines and sports, in a large Swedish dataset that included 61 athletes with 20 or more, 312 athletes with 15 or more and 1147 athletes with 10 or more results, no differences were seen in the rate of decline between events [14]. This corresponds with the observation that the age-related decline in anaerobic an aerobic power did not differ significantly between athletes participating primarily in power or endurance events [32]. Overall, the pattern emerges that the rate of performance decline during ageing is similar for most track and field events, as is illustrated in **figure 1A**.

The first longitudinal data-sets on master athletics and master swimming performance declines were reported in the 1980s [23,33] and made comparisons with the rates of age-related decline seen in cross-sectional data possible. In the Canadian Masters track rankings, the performance decline over a 5-year period was reported to be half as steep in longitudinal than cross-sectional data [23]. Similarly, Young & Starkes [24] found that the age-related decline in running performance in 15 male athletes (1500 m: 7 athletes, 10 km: 9 athletes, one participated in both events) who had been training for 30.6 years (mean; range 19 to 44) was less steep than that seen in cross-sectional data. In a subsequent study by the same group [10] the performance decline in the 200 m sprint, 1500 m and 10 km running in 45 master runners who had continuously trained for at least a decade again showed a slower age-related performance decline than reported for cross-sectional data. The authors suggested that this indicated an attenuation of performance declines due to the engagement in organized sport for lengthy periods. In addition to this, in a 45-year follow-up study of runners who participated in the 1968 Olympics, Everman et al. [34] found that a higher initial fitness was associated with a higher fitness at old age. This shows that performance at high age not only depends on continuous sports engagement, but also on the performance at a younger age.

It is, however, currently unknown if and to what degree continuous exercise in different sports or disciplines attenuates the performance decline rate. Selection effects of the fittest individuals and dropping out of lesser performers may give the false impression that continuous training attenuates the age-related decline in athletic performance. There is some evidence that this bias is minimal as the performance of 80-year-old athletes still performing at the age of 85 did not differ significantly from the performance of those ceased to compete at the age of 85 years [25]. It rather appears that the performance trajectories of athletes and non-athletes converge at very high age [35], as illustrated in **figure 2**. Performance and muscle function declines seem to follow the same pattern during ageing [35]. Interestingly, the variability in performance increased with advancing age in swimming [26], in contrast to the maintained variability during ageing and even a reduced variability after the age of 90 years reported in track-and-field disciplines [25]. Ageing and physical activity have opposite effects on the function of many physiological parameters that play a role in athletic performance, as illustrated in **figure 3**.

Peak performance

The age of peak performance varies substantially among sports, where for instance it is much lower in throwing than long-distance endurance events [15], and in ultra-endurance events, it can even be within the age-range of master sports [36]. In 24h ultra-cycling, for example, the ages of peak performance for women and men were 37.3 ± 8.5 and 38.3 ± 5.4 years, respectively, in a cross-sectional study [37]. The same is true for peak 24h ultra-marathon performance [38].

Despite the early ages of peak performance, the throws are the most popular in the oldest-old athletes. Only very few of the oldest-old athletes still participate in sprinting and running events, even though these disciplines show later ages of peak performance [14,25]. Perhaps, this is explicable by the fact that throws can be conducted from a standing position and require neither running nor jumping, which may make them still feasible when running has become difficult due to sarcopenia and frailty [35]. Interestingly, the age of onset of performance decline acceleration was similar in throwing and other track and field disciplines [25], which indicates that the popularity of throwing events in the oldest-old athletes is not only independent of the peak performance age, but also independent of the age of the onset of performance decline acceleration.

Sex differences

Physical performance of boys and girls is similar until the beginning of puberty at the age of 10-13 years [39,40]. After puberty, however, men outperform women in most sports during adulthood, but sex differences in performance appear to diminish with increasing age. For instance, after the age of 75 years swimming performance was similar in men and women in all distances and disciplines [41]. In contrast to these observations is the larger age-related rate of performance decline in 50-m swimming in women compared to men in a longitudinal data-set [26]. We have no explanation for this discrepancy between studies, but it has been reported that time differences between sexes in swimming are on average smaller than during cycling and running [42], and during anaerobic than aerobic swimming events, suggesting a smaller rate of decline in anaerobic power than cardiovascular endurance in swimmers [26]. However, the decline in aerobic and anaerobic power has been reported to be similar in power and endurance in track and field athletes [32].

Concerning age-related performance declines in women, one recently discovered phenomenon deserves further scientific attention. Huebner et al. [43] studied sex differences in Olympic weightlifting and found that the age-related performance decline of female weightlifters mirrored the decline for men, except for an accelerated decline during a 10-year period around the late 40s to late 50s, thus coinciding with a transition into menopause. In line with this, Ganse et al. [14,15] recently reported that the steepest decline in performance before the age of 60 years occurred in the women's discus and javelin throw. This was not attributable to changing implement characteristics, as the weight of the women's discus is not reduced before age 75, and the weight of the javelin only decreases at age 50. In addition, decreased implement weights would result in an improvement rather than decrement in performance. Causes for the particularly steep declines might be related to hormonal changes and their effects on muscle function or neuromuscular interaction, and need to be addressed in future studies. It is unclear, however, why such accelerated performance declines are not observed in other track and field disciplines, such as shot put or in the jumps.

Performance improvements associated with changes in implements

Decreases in implement weights in throwing disciplines may bias the results of regression statistics and cause sudden upward jumps in performance curves [14,15,44]. The phenomenon also creates potential bias in the hurdle sprints where the height of, and distance between, hurdles decrease with increasing age. Implement specifications are regulated by World Master Athletics (Appendix A-C Hurdles & Implements)[1] and change, as an example, in the female shot put with age as follows: 35–49 years: 4 kg, 50–74 years: 3 kg, 75+ years: 2 kg; men: 35–49 years: 7.26 kg, 50–59 years: 6 kg, 60–69 years: 5 kg, 70–79 years: 4 kg, 80+ years: 3 kg. In addition to this, some implement specifications were changed over the last century, such as a forward shift of the javelin centre of mass to make them drop earlier for men in April 1986 and for women in April 1999, as several athletes had thrown beyond the throwing field in stadiums [45].

Also, improvements in the quality of equipment [46] improved training regimens, tactics, nutrition and technical developments may have improved the performance over time. Technical improvements include those in shoe design, poles for pole vaulting, bicycle technology, and others [47,48]. Such issues need to be considered when interpreting long-term performance trajectories and will lead to an underestimation of the age-related rate of performance decline rather than an overestimation.

The musculoskeletal system in master athletes

Physiology of muscle aging

According to Arampatzis et al. [49], the three main contributors to the reduction in maximal running velocity are 1. a decreased maximum muscle strength, 2. a slower rate of force development and transmission, and 3. a reduction in elastic energy storage and recovery of tendons. During ageing, there is a progressive loss of muscle mass, mainly in the lower body, which increasingly shows up after the age of about 45 years [50]. The absolute decline is faster in men than in women, but the relative decline is similar [51]. The rate of loss of muscle mass in cross-sectional studies amounts to approximately 1% per year, but larger rates of decline have been observed in longitudinal studies [52]. In addition, there is

[1] https://world-masters-athletics.com/wp-content/uploads/2018/03/appendix-WMA-22.03.2018.pdf

an accelerated loss of muscle mass and muscle function with increasing age [53] similar to that seen in performance (See **Table 1**). The declines in force and power generating capacity exceed the loss of muscle mass as reflected by a concomitant decline in specific tension (force per muscle physiological cross-sectional area) [54]. In mice, the reduction in specific tension may even precede the decline in muscle mass [55], and there is some evidence this is also the case in humans [56]. Also the age-related reduction in power generating capacity per unit muscle mass is decreased in old age, as reflected by the progressive loss of muscle power during a countermovement jump that was not necessarily accompanied by a commensurate loss of muscle mass [57,58]. In an older group of men (62 vs. 25 years) training for 7-9 h a week for 10-12 years, it was found that though the age-related decrease in muscle mass could not be stopped by a training programme, the decline in specific tension was prevented [59].

Effects of exercise on muscle mass

Resistance exercise can increase muscle mass and strength at old age [60]. However, the increase in muscle mass in response to resistance training at the same relative intensity in young (22-31 years) and old (62-72 years) individuals was attenuated in the older group (Elbow flexors 22 vs. 9%; Knee flexors 8% *vs.* 1%; Knee extensors 4% *vs*. 6%; increase in Young vs. Old), even though the increase in specific tension (3 repetition maximum (RM) per muscle cross-sectional area) was similar [61]. In another study that tested resistance training for 9 weeks, 3 days a week, there was no difference in the increase in strength between elderly (65-75 years) and young (20-30 years) women, but the older women showed an increase in the number of damaged fibres to 5-17%, which was not observed in the young women [62]. Part of the attenuated hypertrophic response at old age might thus be due to a higher susceptibility to damage at old age. In line with this, it has been suggested that the accumulation of micro-injuries with incomplete repair is one of the factors that causes the age-related decline in specific tension and muscle mass [63].

Chronic low-grade systemic inflammation may contribute to the age-related muscle wasting [64]. The expression of the inflammatory cytokine tumour necrosis factor α (TNFα) in muscle tissue has been shown to be higher in 81- than 23-year-old people, while 3-month resistance training reduced the expression [65]. The rate of protein synthesis in the exercise group was inversely related to the expression of TNFα [65], further suggesting that systemic inflammation is one of the factors that attenuates the hypertrophic response at old age [66].

It has been suggested that regular activity can prevent the age-related loss of motor neurons and motor units, as reflected by a higher number of motor units in the tibialis anterior muscle from master athletes than age-matched non-athletes [67]. However, other studies with a larger number of athletes have shown that the adductor minimi [68], the biceps brachii and vastus lateralis muscle of master athletes do not show any evidence of attenuated loss of motor units [69]. The developing consensus is that regular physical activity cannot prevent motor unit loss, but the larger motor unit size in master athletes than non-athletes is suggested to be a reflection of enhanced axonal sprouting and reinnervation of muscle fibres that became denervated following motor neuron loss [69]. These electrophysiological estimates of motor unit number and size are supported by larger and more abundant fibre type grouping, suggested to be a consequence of reinnervation of denervated fibres by neighbouring axons [70]. However, the latter authors did not consider the potential influence of differences in fibre type composition on the occurrence of fibre type grouping. This is important as it has been observed that the fibre type grouping in the vastus lateralis of young-adult and old athletes and non-athletes was similar to that expected from the fibre type composition [71]. In addition, there was no age-related increase in the size and abundance of fibre type groups, nor where there any differences between master athletes and non-athletes [71]. These observations thus raise the question whether indeed regular physical activity helps to preserve motor neurons and/or facilitate reinnervation of previously denervated fibres. Whatever the final verdict, it appears that the muscles of master athletes are stronger and larger than those of non-athletes, but that the ageing process *per se* is not slowed by regular exercise. Further evidence for the lack of a protective effect of regular exercise on skeletal muscle is the similar proportional age-related decline in power generating capacity in weight lifters and non-athletes [72].

Decreases in flexibility

The range of joint motion, determined by the flexibility of the surrounding tissue and tendons, is another major determinant of sports performance that decreases with age [49,73,74]. The lower tendon stiffness in older than younger athletes will result in a slower force transmission and may result in slower running

[49]. A 43% lower Achilles tendon stiffness compared to younger participants was shown in a study comparing physically active and healthy younger (21 ± 3.25 years) and older (69 ± 2.86 years) adults [75]. Craib et al. [76] hypothesized that a low flexibility in the lower limbs and trunk was associated with enhanced running economy in sub-elite male runners by increasing storage and return of elastic energy and minimizing the need for muscle-stabilizing activity. In sprinters and middle-distance runners, however, a lower hip flexibility was associated with a lower performance and changes in kinematic parameters [77,78]. These included increases in the bending over angle, brake angle and hip flexion angle, and decreases in the propulsion angle and leg stiffness angle during the running cycle with age, which indicates increased joint stiffness [77]. Tendons become more susceptible to injury with age, which is why overhead master athletes (such as throwers) often suffer from rotator-cuff injuries, associated with limitations in the range of motion and pain, and thereby a decreased performance [79]. Interestingly, in a field study at the European Veteran Athletics Championships 2012 the injury rates were higher in the sprints, middle distance and jumps compared to the throws, long distance and decathlon/heptathlon groups, but the low risk of injuries in healthy master athletes did not increase with age or performance [80]. This suggests that perhaps master athletes are aware of their limitations, preventing an age-related increase in the incidence of injuries.

Cardiovascular and pulmonary changes with age

Similar to the decline in skeletal muscle power, the performance decline in ageing is associated with a progressive decrease in cardiovascular reserve. The decrease in maximal oxygen uptake amounts to about 1% per year [81]. High levels of physical exercise along the life span have been suggested to slow the multi-systemic deterioration commonly observed in inactive individuals, and thereby attenuate the age-related VO2max decline [9].

It has been reported that ageing seems to have a greater impact on anaerobic versus aerobic power in trained master athletes [81], but [82] found that both peak anaerobic and aerobic power declined by 7% to 14% per decade and that this rate of decline did not differ significantly between athletic disciplines or sexes.

Climstein et al. [83] investigated cardiovascular risk profiles and discovered that World Master Games participants demonstrated better values in a number of cardiovascular disease (CVD) risk factors when compared to the general population. This included a lower Body Mass Index (BMI), waist circumference (WC), resting blood pressure (BP) and circulating lipid content, and better lipid composition (total cholesterol, high density lipoprotein and low-density lipoprotein). This study is not an observation on its own as in master swimmers, hypertension and obesity were less prevalent compared to controls [84,85] and they also used less medication [85]. These findings reflect the benefits of regular physical activity for health.

Cardiac function

With increasing age, an increase in ventricular stiffness contributes to a worsening left ventricular (LV) diastolic function [86] that is reflected by reductions in early inflow velocity, ratio of early-to-late inflow velocity [87], early diastolic tissue velocity, and increases in the isovolumic relaxation time and the time constant of isovolumic pressure decay [86,88]. Lifelong exercisers have a greater stroke volume and consequently a superior functional capacity and cardiovascular reserve than their sedentary peers [86,89] at least partly attributable to larger left and right ventricular mass and end-diastolic volume [90].

LV compliance showed a gradual decline in healthy sedentary subjects until approximately the age of 64 years, when LV stiffening reached a plateau and was followed by a LV volume reduction [91]. This age-related increase in LV stiffness was prevented by regular training [92,93].

While the ejection fraction of the right ventricle (RV) at rest was similar [90,94], the ejection fraction was higher during maximal exercise in master athletes than non-athletes [94]. As low heart rate variability is a predictor of mortality [95] it is significant that in addition to these morphological and functional parameters master athletes exhibit a higher heart rate variability that reflects a larger ability of the heart to adapt to autonomic signals, such as those elicited by emotions [96]. Lifelong exercise also improved cardiac baroreflex function and thereby blood pressure regulation [97]. If and in which cases increased risks of arrhythmias are caused, or may be attenuated, by life-long exercise is a matter of debate [98]. The potential risk of arrhythmias is reflected by the higher prevalence of atrial fibrillation in endurance master athletes after a long-distance cross-country ski race compared with elderly men in the general population [99].

Blood vessels

Cardiovascular ageing is, among other things, characterized by vascular stiffening, endothelial dysfunction, increases in elastin-collagen content and impaired neurohormonal signalling [100]. In master athletes the stiffness of arteries was less and endothelial function better than in age-matched non-athletes [101,102]. There is, nevertheless, an ongoing debate as to whether high levels of physical activity and endurance training can promote atherosclerotic cardiovascular disease [103], as a higher prevalence of atherosclerotic plaques was found in male endurance athletes, but not female athletes, compared with sedentary non-athletes [104,105]. Other studies on the other hand, have reported fewer plaques in female athletes [106]. In addition, a high prevalence of excessive dilation of the ascending aorta was found in a cross-sectional study on endurance master athletes by echocardiography [107]. These findings suggest that 1) among ageing endurance athletes, clinically relevant aortic dilation is common and probably a result of arterial wall remodelling in response to long-term endurance exercise and 2) exercise may have different effects on the vascular health in men and women, where particularly men may be at risk of developing atherosclerosis.

An age-related reduction in the microcirculation and endothelial dysfunction may also diminish thermoregulation and thereby have a negative impact on performance, particularly in a hot environment. Indeed, old age is associated with impairments in thermoregulation and higher risks of heat-related health issues [108,109]. The Whole-Body Heat Loss (WBHL), the ability to dispose of excess heat, decreases with age and is exacerbated by low cardiorespiratory fitness and high body fat [110] due to impaired skin-vasodilatory responses and sweat gland activity [111-115]. The lower sweat gland activity seems to be a consequence of the impaired vasodilation of the skin vasculature, a lower responsiveness of sweat glands to cholinergic stimuli and a reduced sensitivity of thermoreceptors [116]. Impairments in WBHL are attenuated by regular aerobic exercise [117,118]. In line with this, it has been found that the skin temperature in master athletes participating in the 10 km race of the 2018 World Master

Athletics Championships showed no age-related differences, suggesting that master athletes have no impairment in heat dissipation [119].

Pulmonary function

Physiological lung aging includes reductions in the surface area for gas exchange, enlargement of alveoli without alveolar wall destruction, and loss of alveolar attachments supporting the peripheral airways, often referred to as "senile emphysema" [120]. Functional changes, such as reduced elastic recoil and increased gas trapping result in a progressive decrease in expiratory flow rates with age in otherwise healthy people [120,121]. In a field study at the World Masters Athletics Indoor Championships in 2012, spirometric function was similar in master athletes and age-matched controls, but a better lung diffusion capacity was found in male endurance athletes [122]. Nevertheless, the diffusion capacity of the older athletes was lower than that of the young non-athletes. In another field study at the 2011 French master swimming championships, higher peak expiratory flow values were found in master swimmers, suggesting better lung function [85]. This is unlikely to be a result of training, as in a large population of power and endurance athletes neither age-graded performance nor weekly training hours were significantly related to lung age and there was no evidence for an attenuated decline in spirometry [123].

Conclusions

Physical performance declines with age, and the decline accelerates from about the age of 70 years onwards. A progressive loss of muscle mass, declines in force and power generating capacity, decreased flexibility and a concomitant decline in specific tension characterize the muscular changes underlying performance declines. In the cardiovascular system, cardiac and vascular stiffness and dysfunction underlie the age-related declines in stroke volume and cardiac output that in turn contribute to a decrease in performance. Both the decrease in muscle mass and the decline in maximal oxygen uptake amount to about 1% per year, which is similar to the performance declines in many track and field disciplines. Master athletes have a better performance at any age than non-athletes and have overall a better health than age-matched non-athletes. However, not all is sunshine in master athletes as recent studies have shown that long-term endurance exercise in master athletes is associated with an increased incidence of atrial fibrillation, atherosclerotic plaques and aortic dilation.

Conflict of interest

The authors guarantee, beyond the absence of any conflict of interest, that the manuscript was built based on the IJSM ethical standards [124].

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Table legends

Table 1: Overview of longitudinal performance decline rates in different sports from recent papers. ‡ = the ordinary least squares regression data is reported, * = number of athletes with at least 10 longitudinal data-points that were used to calculate these decline numbers.

Figure legends

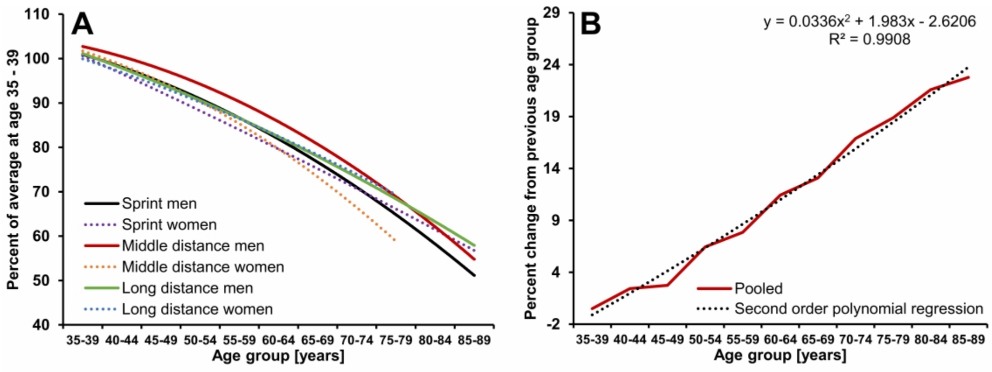
Figure 1: **A:** Second order polynomial regression functions for the pooled data of the sprint (100 m, 200 m, 400 m), middle (800 m, 1500 m, 3000 m) and long distance (5000 m, 10 km), in five-year age groups. The data are shown for men (solid lines) and women (dotted lines) separately. Data from the Swedish Master Athletics database [13] were used to generate the graph. **B:** All spring-, middle- and long-distance data pooled to show the performance decline in percent changes from each previous age group. The percent changes increase with age.

Figure 2: Illustration depicting the approximate decline trajectories of master athletes and non-athletes. The blue arrows indicate performance changes of non-athletes who become master athletes.

Figure 3: Illustration of how ageing and physical activity in master athletics have opposite effects on the function of many physiological parameters that play a role in athletic performance.

Table 1: Overview of longitudinal performance decline rates in different sports from recent papers. ‡ = the ordinary least squares regression data is reported, * = number of athletes with at least 10 longitudinal data-points that were used to calculate these decline numbers.

Reference	Sport, discipline and number of athletes	Age group [years]	Performance decline [%/year] men	Performance decline [%/year] women
Rubin et al., 2013‡ [18]	Swimming 50m (87 men, 85 women)	41 – 50	0.38	0.36
		51 – 60	0.38	0.36
		61 – 70	0.38	0.37
		71 – 80	0.53	1.40
		81 – 90	2.08	3.37
		91 – 100	4.24	5.68
	Swimming 100m (89 men, 114 women)	41 – 50	0.39	0.42
		51 – 60	0.39	0.42
		61 – 70	0.39	0.42
		71 – 80	0.91	0.77
		81 – 90	2.75	3.17
		91 – 100	4.96	6.47
Lepers & Cattagni, 2018 [29]	Running 1500m to Marathon, average decline of one male athlete	65 – 74	0.47	n/a
		70 – 79	0.43	n/a
		75 – 84	0.81	n/a
		80 – 89	1.34	n/a
Sousa et al., 2020 [19]	Swimming athlete A	35 – 55	0.62	n/a
	Swimming athlete B	40 – 69	0.19	n/a
	Cycling athlete A	35 – 55	0.19	n/a
	Cycling athlete B	40 – 69	1.12	n/a
	Running athlete A	35 – 55	0.98	n/a
	Running athlete B	40 – 69	1.34	n/a
Ganse et al., 2020b [14]	Sprinting 100m (48 men, 19 women)*	35 – 69	0.65	0.71
		70 – 94	0.72	1.12
	Sprinting 200m (39 men, 15 women)*	35 – 69	0.75	0.78
		70 – 93	0.94	1.54
	Sprinting 400m (33 men, 14 women)*	35 – 69	0.86	0.67
		70 – 87	2.36	1.81
	Running 800m (44 men, 19 women)*	35 – 69	0.71	0.96
		70 – 91	0.98	1.28
	Running 3000m (9 men, 4 women)*	35 – 69	0.73	0.63
		70 – 86	0.99	n/a
	Running 10km (61 men, 10 women)*	35 – 69	0.69	0.84
		70 – 85	0.95	1.56
	High jump (40 men, 8 women)*	35 – 69	0.88	0.42
		70 – 90	1.12	1.53
	Long jump (34 men, 11 women)*	35 – 69	1.07	1.18
		70 – 91	1.57	1.75
	Discus throw (198 men, 44 women)*	35 – 69	0.79	1.37
		70 – 96	1.59	1.15
	Shot put (159 men, 37 women)*	35 – 69	0.73	1.19
		70 – 96	1.48	0.44
	Javelin throw (130 men, 27 women)*	35 – 69	1.10	1.44
		70 – 96	1.67	1.19



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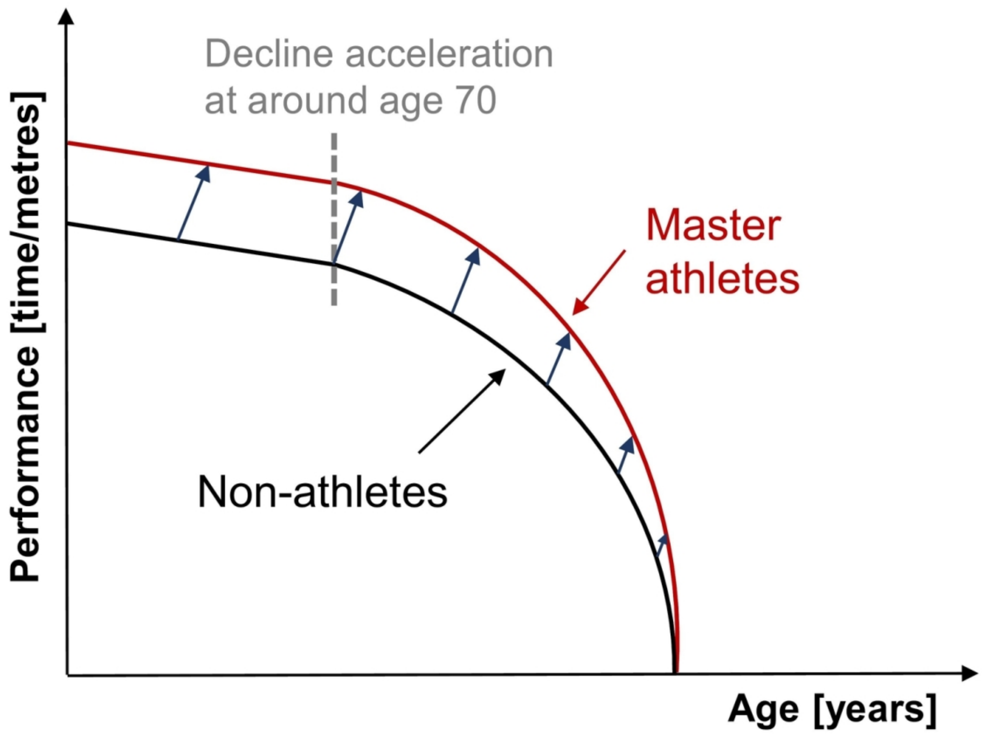

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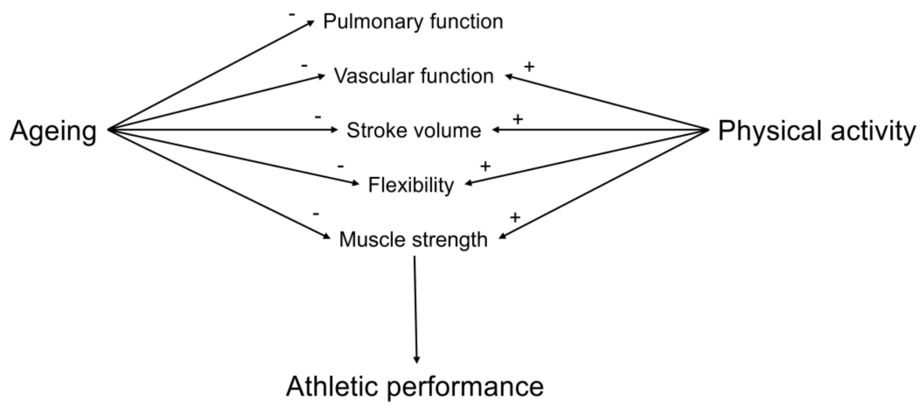

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