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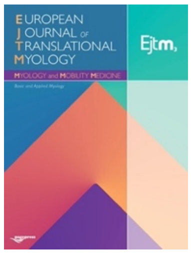

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Changes in physical performance with aging in master athletes and in the general population: an update

Medhi Hassani,[1] Alessandra Renzini,[2] Lam Nguyen,[2] Dario Coletti[2,3,4]

[1]Laboratory ORPHY, IBSAM, Brest University, Brest, France; [2]DAHFMO Unit of Histology and Medical Embryology, Sapienza University of Rome, Rome, Italy; [3]Institut de Biologie Paris-Seine (IBPS), Development, Adaptation and Ageing (Dev2A), Sorbonne Université, Paris; [4]Interuniversity institute of Myology, Rome, Italy

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Abstract

One of the fundamental biological processes underlying aging is the decline in physical performance. Sarcopenia, dynapenia, chronic inflammation, and other factors including the loss of motor units largely account for this decline. Master athletes—individuals who train and compete well beyond early adulthood—represent a valuable model for studying healthy aging. In the general population, physical performance follows a characteristic lifespan trajectory, increasing from childhood to a peak in early adulthood and progressively declining with aging due to a reduction in muscle mass and quality, and in multisystem physiological functions. The seminal studies by Gava and colleagues on master athletes indicate that, under ideal conditions of being disease-free or injury-free, performance loss of these athletes follows an attenuated, linear fashion from early adulthood into advanced age. While lifelong training cannot halt age-related physiological deterioration, it can attenuate the rate of functional decline in cardiovascular, neurocognitive, and musculoskeletal functions. From a sex-based perspective, males demonstrate an absolute advantage in power and strength compared to females, whereas differences in endurance performance are smaller. With age, the physical performance gap between the two sexes tends to narrow, particularly in endurance disciplines. Overall, the master athlete model supports the concept that aging-related performance decay follows predictable biological rules, while its rate remains highly modifiable through sustained physical activity. These insights have important implications for exercise prescription, preventive strategies, and healthy aging.

Introduction

The physical performance of humans, both in terms of power and endurance, increases from childhood to a peak in adulthood and declines in elderly people along with the mass and quality of muscle. Since the slope of the curve during aging makes all the difference for quality of life and compliance with sport activities, many studies focus on the mechanisms of age-related sarcopenia, possible countermeasures, and the effects of exercise in the elderly people. Of particular interest, as a model of healthy aging, is the analysis of Master athletes, who in most cases have exercised in a lifetime.

Seminal papers on this topic were the articles by Gava et al. published in Experimental Aging Research and in European Journal of Translational Myology between 2015 and 2020. Paolo Gava was a sustainable resources engineer, who trained for years as a semi-professional athlete, winning Italian and European short distance races for Master athletes; this led to his scientific interest on the physical performance of aged people.[1] As detailed below, the most striking finding by Gava and colleagues is that in the absence of diseases and trauma the decay of the physical performance in master athletes is linear from 30 to 100 years.[2–4] By using an innovative mathematical approach to analyze Master world records, Gava's group also showed that normalized running parameters of male and female athletes show similar trends of muscle performance decline with aging, suggesting the existence of minimal sex differences in the process.[3] Briefly, for each discipline and age category, performance (e.g., time or distance) was converted into a parameter reflecting the mechanical power required to achieve the result, thereby enabling comparisons across events with different physiological and biomechanical characteristics. Performances were then normalized to the corresponding senior world record, yielding a dimensionless index of relative performance independent of sex, discipline, and absolute values. This approach allows direct comparison of age-related performance decline across sexes and sport disciplines based on a common scale. Using this approach, Gava's group also showed that normalized running parameters of male and female athletes follow very similar trajectories of decline with aging, suggesting that the underlying biological processes are largely shared between sexes.[3] These findings support the concept that, under optimal conditions, age-related performance decline follows predictable patterns that can be robustly quantified through this modeling framework.

The number of papers describing research on "Master athletes" in PubMed markedly increases following Gava's 2015 paper, with a peak a in 2021-22; similarly, Gava's papers published in Eur J Transl Myol on "Master athletes" AND "sex differences" precede most of the papers containing the same keywords (Figure 1)

For all the above, we included the studies by Gava *et al.* in the EJTM Seminal Paper Series and we discussed these results while providing an update of the research on the topic that has been done thereafter.

Changes in physical performance with aging

The growing aging population presents new challenges associated with the need to keep older adults healthy, independent, and active for as long as possible. Preventing and reducing the risk of physical and cognitive decline has therefore become one of the key priorities in public health. Aging is a natural biological process associated with several progressive modifications in muscle function and physical performance.[3,5,6] With advancing age various structural and functional changes occur, affecting the neuromuscular, cardiovascular, and metabolic systems.[7–9] These alterations may become important in elderly people, leading to a significant decrease in strength, power, speed and endurance, ultimately leading to an overall decline in physical performance.[5,10,11]

In this section, we will describe the age-performance relationship in the general population, focusing on the different stages of performance decline with aging. Across the lifespan, physical performance/physical functional capacity typically follows an asymmetrical inverted-U trajectory: it increases from childhood through adolescence, peaks in early adulthood, and then gradually declines into older age (Figure 2).[12]

Indeed, exercise performance is maintained until a certain age, with a peak in the early adulthood (e.g., 30–35 years). Thereafter, performance progressively declines as a result of primary aging combined with external factors such as lifestyle and exposure to environmental pollutants.[12] This pattern of age-related decline has been identified in cross-sectional studies and confirmed in longitudinal ones.[4,13,14] The peak in physical performance that is reached at around the age of 30 reflects an optimal balance between strength, power, speed, and endurance.[3]

Between 30 and 50 years of age, the decline remains modest and gradual, often barely noticeable in daily life or during physical activity.[2,10] This is particularly true for endurance events, where the decrease is very small before the age of 50. The 30-50 years of age period represents a key transitional stage, where age-related changes begin to appear subtly and progressively.[15] Physiologically, several factors explain this early decline. First, there is a progressive loss of fast-twitch muscle fibers, accompanied by fat infiltration into the muscle tissue, fibrosis, and a gradual decrease in overall muscle mass.[16,17] Second, a general decline in endocrine function is observed, including lower blood concentrations of testosterone, Growth Hormone (GH), and insulin-like growth factor-1 (IGF-1).[17,18] Moreover, early neuromuscular alterations, such as a slight reduction in nerve conduction velocity and motor coordination, may occur, although they do not yet have a major impact on overall performance.[17,19] This period from adulthood to the early senior years is often considered an ideal window for prevention, since these early age-related changes remain largely modifiable and manageable. Adopting interventional strategies during this phase has a decisive influence on future physical performance and the trajectory of aging.[20,21] For instance, regular training that combines endurance, strength, and power exercises can help delay the onset of decline and preserve physical function.[22,22,23] In addition, adequate nutrition and optimized recovery strategies play a crucial role in maintaining performance at its highest possible level.
After the age of 50, the decline in peak performance becomes much more pronounced and generally follows a linear pattern. During this period, multiple physiological systems are simultaneously affected, resulting in a marked reduction in overall physical capacity.[24,25] This decline is particularly evident in the progressive loss of muscle mass (sarcopenia),[26,27] strength (dynapenia),[28] and power[29] as well as in the deterioration of cardiovascular and respiratory function. Consequently, the ability to generate force, sustain endurance, and recover efficiently after exertion becomes increasingly limited.[30] Interestingly, the minimal differences observed between men and women at this stage

suggest that the decline is primarily driven by universal biological mechanisms, while modifiable factors such as training, lifestyle, and recovery strategies continue to play a crucial role in mitigating its progression.[25]

In septuagenarians and beyond, the decline in physical performance becomes progressive, sharp, and severe. Indeed, all systems involved in movement and endurance suffer from a marked reduction in their functional capacity.[31] Among crucial events underpinning this decline there are: i) loss of neurons and motor units, which reduces the coordination and the efficiency of muscle contraction;[32,33] ii) chronic low-grade inflammation, often referred to as *inflammaging*, strongly linked to the aging process;[34,35] iii) age-related comorbidities, such as diabetes, cardiovascular disease, and joint pathologies, which further limit mobility and peak performance.[36,37]

Based on all of the above, the performance in different types of physical activities declines with aging, but the rate and onset of decline vary depending on the physiological demands of the activity. Numerous studies have shown that endurance performance, such as in long-distance running or cycling, decreases more gradually and at a later age compared with power- or strength-based activities, such as jumping and throwing sports.[38] Endurance capacity shows a moderate but progressive reduction, primarily due to age-related declines in maximal aerobic capacity and cardiovascular efficiency, particularly after the age of 50.[38] In contrast, activities requiring power and explosive strength exhibit a steeper and earlier deterioration, largely associated with losses in neuromuscular function, motor unit recruitment, and the selective atrophy of fast-twitch muscle fibers. These observations highlight that different physiological mechanisms underpin the decline in various aspects of physical performance.

Such knowledge provides the foundation for targeted interventions — through individualized exercise prescription, nutritional strategies, and therapeutic approaches — aimed at mitigating functional decline, maintaining independence, and enhancing the quality of life throughout aging. In addition, the understanding of mechanisms underlying muscle decline is crucial not only for preventing frailty and preserving autonomy with aging in the general population, but also for optimizing training strategies and maintaining high-level performance in master athletes who continue to train and compete beyond the age of 35.

Master athletes as compared to the elderly general population

Master athletes represent a unique model for studying the effects of aging on the human body. Unlike the elderly general population, who often experience the consequences of a sedentary lifestyle and age-related diseases, master athletes continue to engage in regular, structured, and often competitive physical activity well into older age. This persistent training allows them to maintain higher levels of cardiovascular fitness, muscle strength, and metabolic health as compared to the general population, providing valuable insights into the extent to which physical activity delays or attenuates the physiological decline associated with aging.[39,40] Therefore, comparing master athletes to the elderly general population highlights the powerful influence of lifelong exercise on preserving functional capacity and overall health during the aging process (Figure 2).

By maintaining regular high-intensity training, master athletes typically preserve higher levels of aerobic capacity, muscle mass, and neuromuscular function than their sedentary peers. For example, Tanaka and Seals,[38] reported that endurance performance and maximal oxygen uptake (VO_2max) decline by about 5% per decade in active older adults, roughly half the rate observed in untrained individuals (Figure 2). Similarly, Pollock *et al.*[41] found that masters endurance runners maintained a significantly greater stroke volume and maximal cardiac output compared with age-matched sedentary adults. Nevertheless, aging still leads to reductions in maximal heart rate, muscle cross-sectional area, and power output, even in highly trained individuals.[42] Overall, being a masters athlete provides a considerable "buffer" against the effects of aging, resulting in a slower and later decline in performance compared with the general elderly population, particularly in endurance-based activities.

The analysis of Masters World Records led by Gava *et al.* shows that peak performance for master athletes remains stable until about 50 years of age. In running events, from sprints to marathons, the decline is minimal, whereas in power-based events such as jumping and throwing, peak performance begins to diminish slightly earlier. After normalizing the data, the analysis of performances from male and female master athletes revealed almost no differences between sexes in this age range — see below for more details on sex differences. This suggests that the initial decline is primarily driven by biological processes rather than sex-specific factors.[2,3]

Several more recent studies have further described the effects of aging on physical performance in master athletes. In a longitudinal study including 89 male and female master athletes of both power and endurance disciplines the authors reported a progressive decline in peak relative power, relative force, and jump height over a mean follow-up of 4.5 ± 2.4 years, without significant sex-by-time or discipline-by-time interactions; these findings suggest that the rate of decline was broadly similar between men and women and between athletic specializations.[43] In parallel, a 10-year follow-up study in male master sprinters aged 40 to 85 years showed that continued sprint and strength training was associated with the improvement, of tibial bone properties, whereas a lower training level was associated with a deterioration in bone traits. More specifically, the best-trained athletes maintained distal tibial bone characteristics and even improved some mid-tibial parameters, supporting the view that regular and intensive exercise can partially counteract skeletal aging later in life.[44] MRI-based studies have shown that male master athletes display greater muscle volumes and lower muscle fat fraction than older non-athletic controls, although their muscular profile remains sub-optimal as compared to that of young athlete.[45]

Overall, these studies suggest that long-term training substantially attenuates — but does not eliminate — the physiological decline associated with aging.[43–45]

Brain integrity, neurocognitive function, neuromuscular efficiency, cardiovascular function and bone density are actively maintained through regular and structured training, thus delaying many of the decline processes typically associated with aging (Figure 3).

Neurocognitive function

From a neurocognitive perspective, age is the main factor contributing to the structural and functional deterioration of the brain, and the risk of dementia increases significantly after the age of 65.[39] Other neurologic markers also progress with age, such as a decrease in total cerebellar volume (approximately 3% per decade)[46] and an increase in white matter volume, which is associated with a slower cognitive processing and a progressive alteration in the integrity of neural fibers. The using of regular exercise, particularly endurance activities, is considered a major protective factor that can slow down the cognitive decline, thus reducing the onset of dementia.[46,47] Neuroimaging data have confirmed several benefits in endurance master athletes. They show a higher cortical brain volume, particularly in motor and spatial areas, and fewer white matter lesions compared to the general population.[48–50] In master athletes, the integrity of motor-related fibers is better preserved, especially among those engaged in endurance training. Regular endurance exercise appears to improve regional cerebral perfusion and certain cardiovascular regulatory mechanisms linked to brain function, thereby slowing the reduction in cerebellar volume associated with aging.[51,52]

Neuromuscular function

Dynapenia is the decline in muscle function due to neural and muscular changes.[53] Numerous studies agree that muscular function is relatively well-preserved during ageing in master athletes, although long-term data on dynapenia in comparison to the general population are still lacking.[32,54–56] Sarcopenia is a major cause of dynapenia in master athletes, largely driven by the selective atrophy of fast-twitch fibers.[28] Consequently, maximal power is disproportionately impaired compared to maximal strength. At the molecular level, age-related declines in speed, power, and strength are accompanied by post-translational modifications of contractile proteins.[57] Moreover, skeletal muscle from master athletes shows lower levels of reactive oxygen species (ROS) and a more efficient antioxidant system,[58,59] suggesting a potential beneficial effect due to lifelong training. Several studies have demonstrated a decrease in α-motor neurons in the dorsal root of the spine when comparing younger men with older men, leading to a loss of around 50-60% of motor units in the quadriceps.[32,60] This event triggers a compensatory reinnervation which increases the size of motor units leading to clustering of muscle fibers of the same type within the muscle, resulting in a slowing of muscle twitches and in a decrease in distal axonal conduction speed.[61] The frequency of maximal discharge of α-motor neurons tends to decrease with ageing, although this decline appears to be attenuated by resistance training.[62] However, voluntary activation capacity remains higher in master athletes compared to the general population, suggesting that the age-related decline does not fully account for the dynapenia observed.

Muscular system

Ageing is associated with a decrease in skeletal muscle mass, strength, and function.[63] In the general population, isokinetic muscle strength decreases linearly with age in men, reaching about 54–89% of the 25-year-old reference value at 75 years, and from 48–92% in women between 40 and 75 years.[64] Long-term training of elderly people counteracts the age-related decline in muscle strength and power.[65] The vertical jump, a simple test, shows a drop in maximal output of about 60% at 70 years of age.[5] In master athletes, the data show that the loss of power and strength is like that of the general population; however, the initial level is higher in master athletes.[66] Sprinters perform better than the general population at all ages, as do endurance runners. Studies on weightlifters and cyclists confirm this trend.[67] Importantly, some parameters, such as strength level and fast contraction capacity, decrease with ageing but can be improved through resistance training, even in old age.[68] The reduction of muscle mass is moderate in master athletes (≈ 4–5% per decade).[69] Fat mass tends to increase with age but remains lower compared to the general population. Therefore, master athletes show a decline with ageing, but they maintain a f higher functional capacity than that of the general population at all ages.[67]

Cardiovascular function

In healthy humans several cardiovascular functions remain stable with aging, such as ejection fraction, heart rate, stroke volume, and cardiac output at rest. However, limb blood flow and vascular conductance progressively decrease, partly due to increased sympathetic vasoconstrictor activity.[70] This reduction can contribute to glucose intolerance, dyslipidemia, and impaired vasodilation during exercise, rest, heat exposure, or hypoxia.[36,71] In parallel, enlargement of the left atrial volume, and arterial aging is associated with structural remodeling, such as myocardial hypertrophy Intima-Media Thickening (IMT) linked to smooth muscle cell hypertrophy and matrix remodeling (higher and lower amounts of collagen and, respectively elastin), even in the absence of atherosclerosis.[72] During maximal effort, VO_2 max decreases by about 10% per decade, in parallel with the decline in maximal cardiac output, due to reduced heart rate, stroke volume, and arteriovenous oxygen difference.[66] The maximal heart rate decreases by about 7 beats per minute per decade. Cardiac atrophy and wasting[73] is considered a major factor underlying the decline in stroke volume and blood volume with age.[74] In master athletes, several studies have shown that the decline in VO_2 max is like that of the general population, averaging about 10% per decade.[66,74] This reduction is primarily explained by a decrease in systolic stroke volume with aging. Regarding peripheral vascular resistance, endurance-trained master athletes do not appear to attenuate carotid IMT remodeling,[75] which increases with aging, but training has been shown to reduce femoral IMT. Moreover, endurance-trained master athletes exhibit a reduced stiffness of central arteries, which is explained by lower vasoconstrictor tone and reduced oxidative stress.[76] Importantly, some cross-sectional studies have reported potential risks associated with long-term endurance training in master athletes, such as a higher prevalence of atrial fibrillation and increased coronary artery calcification scores compared with the general population.[77,78] Despite these risks, master athletes generally maintain superior cardiovascular functional capacity and a more favorable prognosis compared to sedentary peers.[79]

Bone loss

Bones are the other major component of the musculoskeletal system, thus, the quality and preservation of bone tissue impact on physical performance of the elderly people. Bone loss is another natural and progressive aspect of aging occurring when the rate of bone removal (*i.e.* resorption) exceeds the rate of new bone formation. This imbalance leads to decreased Bone Mineral Density (BMD) and compromised bone quality, ultimately resulting in osteoporosis.[80–82] In the general population, ageing leads to a progressive loss of bone tissue and osteoporosis, in turns, increases the risk of bone fractures and the associated morbidity. Physical exercise, particularly activities involving impact or mechanical resistance, stimulates bone adaptation through mechanical loading and improves bone solidity. On the contrary, activities with low mechanical load, such as swimming or cycling, do not show significant effects.[83,84] In master athletes, several reports show specific benefits in certain bone areas, particularly in bones that bear high mechanical stress, such as the tibia and humerus.[85,86] Sprinters and powerlifters display higher bone density and strength compared to endurance runners or the general population at all ages. However, this advantage tends to decrease with advanced age, as the protective effect does not completely prevent the loss of bone density.[87] Eventually, it seems that the best strategy to maintain high bone density is to engage in physical activity early in life.[86,88,89]

In summary, the comparison between master athletes and the general aging population clearly highlights the protective effects of lifelong physical activity on multiple physiological systems. Although aging inevitably leads to a gradual reduction in performance and physiological capacity, master athletes demonstrate protective benefits of sustained physical activity against the typical physiological decline associated with aging; this, in turn, contributes to the maintenance of a high level of functional ability and quality of life throughout advanced age.

Sex difference in physical performance and its decay with age

With aging, both sexes experience a progressive decline in neuromuscular function, including a decrease in muscle mass (sarcopenia), loss of fast-twitch fibers, reduced nerve conduction velocity, and alterations in motor control.[32] However, the mechanisms underpinning this phenomenon appear to act differently between the sexes.[34,35] It is generally believed that women experienced a faster and more pronounced decline in physical activity due to their lower initial muscle mass and hormonal changes, such as the drop in estrogen levels after menopause (Figure 4).[32,90]
Among master athletes, women often show smaller age-related declines in relative endurance capacity and fatigue resistance during submaximal exercise, whereas male master athletes tend to experience steeper reductions in muscle strength and power with age. These differences may be partly related to a preferential loss of fast-twitch fibers and to age-related changes in sex hormones such as testosterone.[91] The postmenopausal estrogen decrease accelerates the loss of lean body mass and increases fatigability, which partly diminishes the female advantage.[92] Overall, sex differences in master-athlete performance appear to narrow with advancing age in some datasets (especially in endurance). In their analysis of Masters World Records in track, jumps, and throws, Gava *et al.* transformed each record into a parameter proportional to the power produced and then normalized performances to the corresponding senior (open) world record for each discipline. With this approach, the usual absolute female–male performance difference (often ~10–15% in raw records)

largely disappears after normalization, meaning that women and men show very similar age-related decline trajectories rather than markedly different “decay rates”.[2,3] Their normalized curves show a decline that is very gentle from ~30 to 50 years, becomes almost linear from ~50 to 70, and then turns progressively steeper at older ages, with male and female slopes nearly overlapping up to ~50 years and showing small divergences thereafter. They also report that disciplines relying more on explosive power (jumps/throws) decline faster than running events in both sexes.[3]
Interestingly, male master athletes, particularly in power-based sports, may experience earlier declines in muscle mass and strength, whereas female athletes generally show lower sarcopenia prevalence than in the general population when adjusted for body size and muscle mass, reflecting sex and specialization effects.[43]
The sex difference in peak performance between male and female master athletes is largely rooted in anatomical, hormonal, and metabolic factors. On average, masculine athletes have greater muscle mass, a higher proportion of fast-twitch fibers, and higher glycolytic enzymatic activity—features strongly influenced by higher testosterone levels—which confer an advantage in strength, speed, and power. In contrast, women tend to display a more oxidative profile with a relatively greater proportion of slow-twitch fibers, which can support better fatigue resistance during sustained, submaximal efforts.[93] These biological differences are reflected in the performance gap: it is typically smaller in endurance events and larger in activities requiring maximal force, speed, or power (often reported around 30–50%).[94] Indeed, female athletes generally exhibit greater resistance to fatigue compared to male athletes in endurance events. This advantage is also observed during the recovery phase; for example, in repeated sprint exercises or dynamic contractions, women often show faster recovery of power and strength.[91,95] This difference is reversed under certain conditions. For instance, during high-intensity efforts, explosive exercises, or eccentric contractions, female athletes may experience a similar or even greater level of fatigue due to their lower initial strength-producing capacity.[91] Hormonal status and genetics affect muscle composition, contractile properties, and energy metabolism accounting for some of the sex differences. The gap between sexes has narrowed over time, particularly in endurance sports, likely driven by social and behavioral factors such as increased female participation, improved training methodologies, and better sex-specific programming.[2,3,5] As a consequence, women’s records have continued to improve in events such as the marathon, where the sex difference has stabilized around ~9–10% versus ~20% several decades ago.[96–98]
Sex differences are also observed in fatigue and recovery, but they are highly task specific. Women generally exhibit greater resistance to fatigue during endurance tasks and often recover strength or power more rapidly in repeated sprint or dynamic contraction protocols.[91,94] Hormonal status and genetics modulate muscle composition, contractile properties, and energy metabolism; in particular, estrogens have been proposed to exert protective effects on muscle membranes and fibers, facilitating recovery and limiting structural damage.[96] As mentioned above, when age-related performance trajectories are examined after appropriate normalization (e.g., relative to senior/open world records), Gava *et al.* reported that male and female decline curves are remarkably similar—especially in endurance—suggesting that the mechanisms driving age-related performance loss are largely shared across sexes. In power and explosive events, female athletes showed a slightly earlier decrease compared to male athletes, but the overall rate of decline remained comparable. These findings suggest that the mechanisms underlying age-related performance loss are primarily biological and largely shared by the two sexes. In contrast, in activities requiring force, speed, or

power, the gap remains larger (30–50%), as hormonal and structural factors play a more significant role in this type of performance.[94] Overall, the trend shows a global reduction in the performance gap between males and females depending on the type of effort: female master athletes perform closer to men in endurance events but remain behind in maximal power performances.[40]
Pharmacological strategies have been explored to mitigate the age-related decline in anabolic hormones, although their effects on performance-related outcomes remain context-dependent. In postmenopausal women, hormone therapy appears to have, at most, a small and inconsistent impact on muscle strength, with meta-analyses reporting either modest benefits or no overall significant improvement.[99,100] In older men with unequivocally low testosterone, testosterone replacement therapy increases lean mass and can yield modest improvements in physical function and indices of muscle power in randomized trials, although the clinical meaningfulness of these gains and the risk–benefit balance require careful individual evaluation.[101,102] By contrast, exercise—particularly resistance training—remains the cornerstone intervention: while resistance exercise elicits robust acute endocrine responses, long-term training generally has negligible effects on resting testosterone concentrations in eugonadal men, yet it reliably improves strength and power through neuromuscular and muscle-specific adaptations and may increase anabolic mediators such as circulating IGF-1.[103–105] Worth noting testosterone use has substantially expanded beyond strictly medical indications in some countries, notably the United States, where prescribing patterns have been influenced by broader men's health/anti-aging practices and direct-to-consumer marketing, with subsequent changes following regulatory safety communications.[106,107] Even sport and fitness environments have been affected by non-medical androgen use, with the aim to improve appearance and/or performance, which represents a distinct issue from clinically indicated hormone replacement.[108,109] In competitive sport, exogenous testosterone remains prohibited under anti-doping regulations, with only tightly regulated exceptions via Therapeutic Use Exemptions (TUEs) for clearly documented endocrine disease, making the boundary between legitimate therapy and doping particularly sensitive.[110]

Conclusions

Human physical performance follows a lifespan trajectory in which power and endurance increase from childhood to a peak in early adulthood and then decline as muscle mass and quality progressively deteriorate. A key message emerging from the seminal work of Gava *et al.* and from subsequent studies is that, in the absence of major disease and trauma, the age-related decay of performance in Master athletes follows a simple pattern, with an approximately linear decline across a broad age range and only minimal sex differences after appropriate normalization. As summarized in Figure 2, this decline reflects the degradation of multiple physiological systems, including neuromuscular function (sarcopenia/dynapenia and preferential loss of fast fibers with disproportionate impairment of power), cardiovascular and respiratory capacity (notably the progressive reduction in VO_2max), bone integrity, and brain-related determinants of motor control and cognition.
Importantly, the comparison between Master athletes and the general aging population supports the concept that lifelong physical activity preserves functional reserve across systems, thereby delaying the transition from performance decline to a clinically relevant disability. While aging is inevitable, the slope of this decline remains, to a significant extent, modifiable—especially when preventive strategies are initiated early (e.g., in the 30–50-year window) and maintained consistently over time.

In this respect, exercise combining endurance, resistance, and power-oriented components stands out as the most robust and broadly applicable intervention, whereas pharmacological approaches aimed at age-related endocrine decline require careful, individualized consideration and should not be viewed as performance-oriented solutions. In addition, exercise programs can be optimized with age: as aerobic capacity declines, emphasis should shift toward maintaining muscle mass, strength, and power through resistance training, high-intensity intervals, and functional exercises. Tailoring programs to individual ability, sex, and sport specialization helps preserve endurance and musculoskeletal function while lowering the risk of sarcopenia and functional decline. Master athletes represent a powerful "model" of successful aging, but they also highlight unresolved questions that warrant future research: disentangling training effects from selection/survivorship bias; improving longitudinal datasets (including women and diverse disciplines); quantifying the roles of injury, recovery, nutrition, and psychosocial factors; and clarifying potential long-term cardiovascular trade-offs reported in highly endurance-trained older athletes.

Overall, integrating mechanistic insights from muscle, heart–vessel, bone, and brain aging with real-world performance outcomes will help refine individualized, evidence-based prescriptions to preserve mobility, independence, and quality of life throughout aging—both in Master athletes and in the broader population.

List of Abbreviations:
GH, growth hormone
IGF-1, insulin-like growth factor-1
ROS, of reactive oxygen species
IMT, intima-media thickening
BMD, bone mineral density
TUEs, Therapeutic Use Exemptions

Correspondence

Alessandra Renzini, DAHFMO Unit of Histology and Medical Embryology, Sapienza University of Rome, Italy.

Tel.: +39 0649766577

E-mail: alessandra.renzini@uniroma1.it

0000-0002-4265-7188

Email addresses and ORCID iD:

medhi.hassani@univ-brest.fr

0000-0001-6498-1344

nguyen.2033442@studenti.uniroma1.it
0000-0002-9831-7959

ugo.carraro@unipd.it
0000-0002-0924-4998

dario.coletti@uniroma1.it
0000-0001-7373-1953

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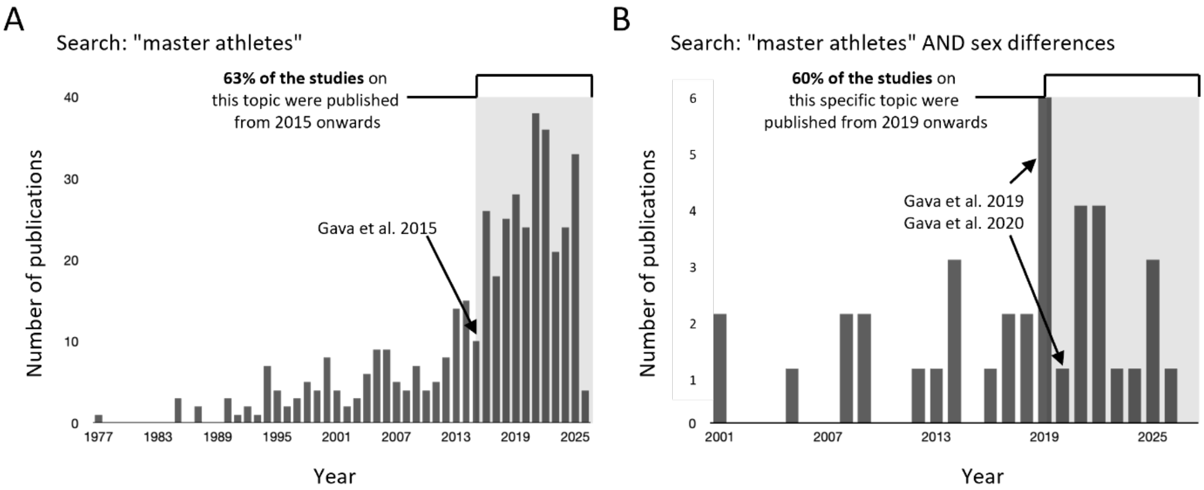

Figure 1. Research trends on the topic of master athletes

Data from PubMed reveal a substantial rise in scientific publication containing the indicated keywords (Search) following Gava's works, with 63% (A) and 60% (B) of the studies published since 2015 and 2019.

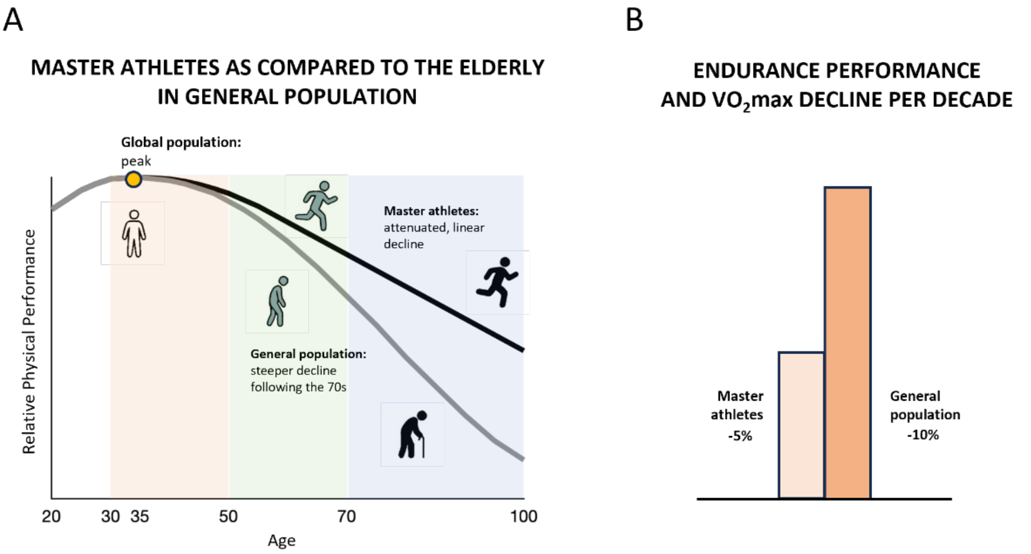

Figure 2. Age-related decline in physical performance: master athletes vs the general population

(A) Relative physical performance peaks in early adulthood and subsequent declines with age in both master athletes and the general population. Master athletes exhibit an attenuated, linear decline compared with the steeper decline observed in the general population, particularly after the age of 70. (B) Endurance performance and VO_2 max decrease with aging in both groups, but the rate of decline in master athletes is half that observed in untrained peers.

Master Athletes: Attenuated Decline		General population: Accelerated Decline	References
Higher cortical volume, slower cognitive decline.	*Neurocognitive*	Faster cognitive decline, lower cortical volume.	39, 46-52
Higher initial strength, moderate mass reduction (4-5% per decade).	*Muscular*	Significant muscle and strength loss.	5, 63-69
Superior capacity; potential risk of atrial fibrillation.	*Cardiovascular*	Reduced capacity, increased arterial stiffness.	66, 70-79
Higher density, especially from high-impact sports.	*Bone Density*	Decreased bone density (Osteoporosis risk).	80-89

Figure 3. System-specific effects of aging

Aging is associated with functional decline across multiple physiological systems; however, this process differs between master athletes and the general population. Master athletes show a better preservation of multiple systems: benefits include a higher cortical volume with slower cognitive decline, a lower muscle and strength loss, and maintained cardiovascular capacity in spite of the potentially increased risk of atrial fibrillation; they also exhibit higher bone density, particularly with lifelong participation in physically challenging activities.

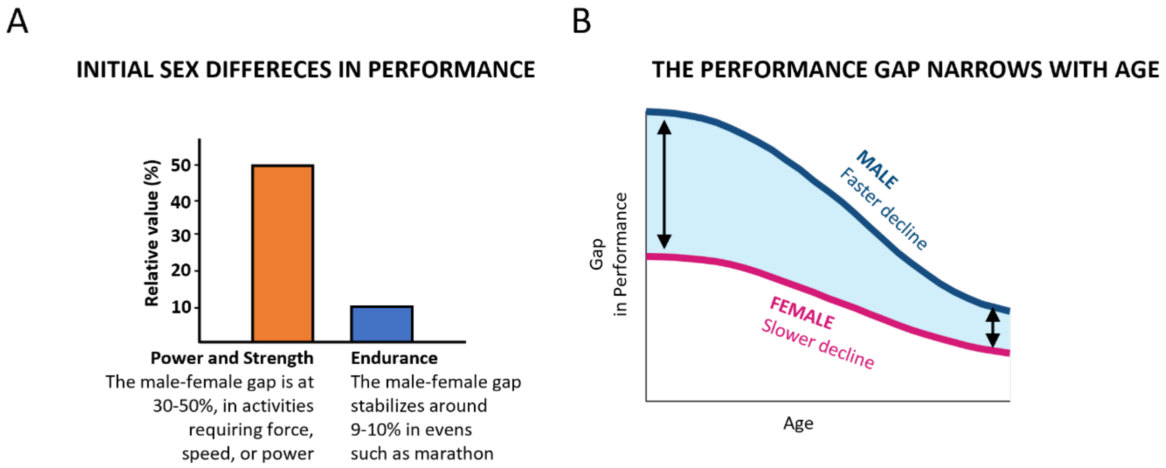

Figure 4. The impact of sex on physical performance

(A) Males have a performance for power and strength (largely due to the higher level of Testosterone) which is approximately 30-50% higher as compared with female. In contrast, this difference decreases to around 9-10% in endurance activities, reflecting the great fatigue resistance in female, which is associated with estrogen and a higher proportion of slow-twitch muscle fibers.

(B) The gap between male and female performance narrows with ageing, particularly in endurance events, as men's performance tends to decline faster.