

Can physical activity ameliorate immunosenescence and thereby reduce age-related multi-morbidity?

Duggal, Niharika; Niemiro, Grace; Simpson, Richard; Harridge, Stephen; Lord, Janet

DOI:

[10.1038/s41577-019-0177-9](https://doi.org/10.1038/s41577-019-0177-9)

License:

Other (please specify with Rights Statement)

Document Version

Peer reviewed version

Citation for published version (Harvard):

Duggal, N, Niemiro, G, Simpson, R, Harridge, S & Lord, J 2019, 'Can physical activity ameliorate immunosenescence and thereby reduce age-related multi-morbidity?', *Nature Reviews Immunology*, vol. 19, no. 9, pp. 563-572. <https://doi.org/10.1038/s41577-019-0177-9>

[Link to publication on Research at Birmingham portal](#)

Publisher Rights Statement:

Checked for eligibility: 27/06/2019

This document is the Author Accepted Manuscript version of a published work which appeared in its final form in *Nature Reviews Immunology*. The final version of record can be found at: <https://doi.org/10.1038/s41577-019-0177-9>.

This document is subject to Springer Nature re-use terms: <https://www.springer.com/gp/open-access/authors-rights/aam-terms-v1>

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

The ageing immune system: can physical activity ameliorate immunosenescence and thereby reduce age-related multi-morbidity?

Niharika A Duggal¹, Grace Niemiro², Stephen D.R. Harridge³, Richard J Simpson^{2,4,5}, Janet M Lord^{1,6}

¹MRC-ARUK Centre for Musculoskeletal Ageing Research, Institute of Inflammation and Ageing, University of Birmingham, UK; ²Department of Pediatrics, University of Arizona, Tucson, AZ, USA; ³Centre for Human and Applied Physiological Sciences, King's College London, UK; ⁴Department of Nutritional Sciences, University of Arizona, Tucson, AZ, USA; ⁵Department of Immunobiology, University of Arizona, Tucson, AZ, USA; ⁶NIHR Birmingham Biomedical Research Centre, University Hospital Birmingham, UK.

Abstract

Remodelling of the immune system with age — immunosenescence — is a significant contributor to poor health in older adults, with increasing risk of infections, cancer and chronic inflammatory disease contributing to age-related multi-morbidity. What is seldom considered when examining the immune response of an aged individual is that the immune system is profoundly influenced by physical activity. Habitual physical activity levels decline with age, with significant consequences for muscle mass and function. Skeletal muscle is a major immune regulatory organ and generates a range of proteins, termed myokines, which have anti-inflammatory and immunoprotective effects. Several studies indicate that maintaining physical activity has immune benefits in older adults; for example, it reduces the systemic inflammation associated with chronic age-related diseases. Herein we discuss how physical activity can prevent or ameliorate age-related multi-morbidity by boosting immune function and consider whether physical activity could improve immunotherapy outcomes in age-related conditions such as cancer.

[H1] Introduction

There is a continuing trend for increased human life expectancy across the globe, particularly in the developed countries¹. Between 1990 and 2010, life expectancy in the UK increased by 4.2 years in men and 1.9 years in women, but **healthy life expectancy [G]** did not keep pace, increasing at approximately half this rate². We are thus living longer, but not healthier. Furthermore, ill health in old age is typically not due to any one disease, but instead many older adults are multi-morbid – defined here as the presence of two or more chronic conditions. For example, in a retrospective study of disease incidence in Minnesota from 2005-2010, 22% of adult patients overall had two or more conditions and this rose to 77% in the over 65 year old group³. Understanding the drivers of age-related multi-morbidity and developing interventions to prevent or delay its occurrence is now a priority in many countries.

It is often not appreciated that increased population longevity is a relatively recent phenomenon, beginning around 250 years ago⁴. This is a relatively short time in the context of our genetic heritage, where our global physiology and accompanying immune system evolved to meet the demands of an active hunter–gatherer lifestyle⁵ (**Figure 1**). Our modern lifestyle goes against the blueprint laid down by this genetic inheritance, with inactivity and overeating resulting in impaired function across a range of systems in old age⁶, culminating in multi-morbidity and increased incidence of cardiovascular disease, obesity, type 2 diabetes and cancer⁶. Thus it is becoming increasingly clear that being sufficiently physically active across the life course is a central requirement for achieving a healthy old age⁷. Moderate to vigorous physical activity and cardio-respiratory fitness are both key predictors for reduced all-course mortality^{8,9}, and the reverse is true for sedentary behaviour such as sitting or lying down^{10,11}. Indeed, large cohort studies have revealed that physical activity and time spent being sedentary are independent variables affecting health and the ideal is to maintain adequate levels of physical activity and minimise sedentary time¹¹. Unfortunately, physical activity tends to decline dramatically with age. For instance, less than 10% of UK adults aged over 65 meet the Chief Medical Officer’s recommendation for physical activity of 150 minutes of aerobic exercise a week. Further, as the immune system is readily influenced by physical activity¹², increased inactivity across the lifespan may also contribute to reduced immunity in old age.

In this Review, we discuss the evidence suggesting that reduced physical activity with age is a major contributor to age-related immune decline, which in turn pre-disposes the individual to multi-morbidity. Physical activity and exercise are often used interchangeably (see Box 1). Here, physical activity is used to refer to the sum of any general body movement that raises energy expenditure above a basal level, whereas exercise denotes a specific form of physical activity, such as cycling or swimming, carried out for a set purpose. We consider active skeletal muscle as a major immune regulatory organ, with inactivity and **sarcopenia** [G] providing a mechanistic link between low levels of physical activity, age-related immune decline and the chronic diseases of old age. The potential of physical activity as an immune adjuvant to enhance responses to vaccines and immune-based cell therapies in older adults is also discussed.

[H1] Physical activity and immune health

An optimally functioning immune system is central to health, with cellular and humoral immunity required for protection against infections, responses to vaccines, detection and removal of cancers, and prevention of autoimmune disease. The immune system does not operate in isolation and is profoundly influenced by environmental factors, including physical activity¹². Consequently, an association between physical activity, immunity and disease has been demonstrated in a range of population-level studies. Participation in regular bouts of moderately intense physical activity (for example, brisk walking or swimming), of at least 150 minutes per week, confers protection against a myriad of immune and inflammatory disorders, as well as multi-morbidity and mortality¹³⁻¹⁵. Prospective studies have consistently shown that regular physical activity reduces the risk of infection^{16,17} and the burden of latent viral infections¹⁸. There is also ample evidence that physically active lifestyles reduce the risk of cancer, particularly those that disproportionately afflict older individuals, such as breast, colon and prostate cancer¹⁹. The benefits of physical activity are also apparent in older adults in the context of protection against frailty and cognitive impairment^{20,21}. We therefore suggest that many of the benefits of physical activity on health are achieved through positive effects on the immune system.

An emerging body of work in animal models and humans also supports causative links between increased physical activity and disease prevention and management mediated by improved immunity. Rodent models have shown that moderate exercise can improve survival in mice infected with a lethal dose of influenza virus²². Here, protection was attributed to a reduction in inflammatory cell infiltration and a shift from a T helper 1 (Th1)- to a Th2-type cytokine profile in the lung²³. Influenza and pneumonia remain major causes of death amongst older adults and prophylactic vaccination is less effective in this population, especially in those who are frail²⁴. Exercise interventions have been shown to improve immune responses to both novel and recall antigens in seniors²⁵, with two clinical trials in aged humans showing that increased physical activity can improve immune responses and extend protection provided by the influenza vaccine^{26,27}. Exercise interventions have also been shown to improve disease symptoms in a range of inflammatory and autoimmune disorders, with the benefits seen including improvements in micro- and macrovascular function²⁸ and decreased disease severity and pain in patients with rheumatoid arthritis²⁹. Consequently, there is increasing interest in whether physical activity can preserve immunity into old age and thereby protect against multi-morbidity.

[H1] Ageing and immunity

The decline in immunity with advanced age has been termed 'immunosenescence' and contributes significantly to ill health in old age. For example, immunosenescence is associated with reduced efficacy of vaccinations³⁰, increased susceptibility to viral and bacterial infections³¹, re-emergence of latent viruses (such as varicella zoster virus, which causes shingles³²) and reduced immune surveillance potentially contributing to increased cancer incidence³³. Another aspect of ageing that is, in part, influenced by immunosenescence is the increase in systemic inflammation, so-called 'inflammageing'. Inflammageing is likely a generic driver of age-related multi-morbidity as the degree of inflammageing has been related to increased risk of most chronic diseases of old age^{34,35}. Indeed, the influence of an active lifestyle on health in old age may lie in its impact upon inflammageing, as regular physical activity has been associated with reduced systemic inflammation in older adults^{36,37}.

[H2] Key features of the immune system in older adults.

Advanced age is associated with remodelling of both the innate and adaptive arms of the immune system which can eventually lead to compromised immunity and disease. As there have been many comprehensive and recent reviews of the changes to the innate and adaptive immune systems with age, we have summarised the key features of immunosenescence in **Table 1**. Key elements include: compromised migration and anti-microbial function in neutrophils and monocytes, reduced natural killer (NK) cell cytotoxicity, reduced quality and quantity of antibody production by B cells, thymic atrophy and increased frequency of highly differentiated T cells that are often considered to be senescent due to their reduced proliferative capacity. Interestingly, these highly differentiated memory T cells³⁸, as well as memory B cells³⁹, exhibit secretion of pro-inflammatory cytokines similar to the **senescence associated secretory phenotype (SASP)** [G] seen in non-immune senescent cells, thereby contributing to **inflammageing** [G].

Crucially, studies in both mice⁴⁰ and humans⁴¹ have identified a suite of immune parameters as markers of biological age, suggesting that immunosenescence is an integral component of the ageing process and a driver rather than a consequence of age-related disease. In support of this proposal, several features of T cell immunosenescence are seen in the early stages of rheumatoid arthritis with no association with the duration of symptoms⁴², suggesting that immune ageing precedes rheumatoid arthritis rather than being a consequence of disease. Furthermore, other chronic inflammatory diseases that occur in childhood, such as spondyloarthropathies, do not show accelerated immunosenescence⁴³.

[H2] Lifelong physical activity and amelioration of immune ageing.

The contribution of the age-related decline in physical activity to immunosenescence has received little attention but is likely to be a significant confounder in studies of immunity in older adults. The effects of maintaining physical activity throughout adulthood on immune ageing also remain largely unexplored as most studies of the 'long term' effects of increased physical activity have only lasted for 6-12 months. To address this issue, one study assessed immune cell phenotypes in physically active male and female non-elite cyclists (n=125) who had maintained a high level of physical activity for much of their adult lives. These older

adults, aged 55-79 years, showed few of the changes in physiological function routinely reported with advancing age, such as loss of muscle mass and function (sarcopenia), reduced insulin sensitivity, elevated cholesterol and high blood pressure⁴⁴. The cyclists also showed few signs of immunosenescence, including reduced evidence of a decline in thymic output, with a frequency of recent thymic emigrants similar to that seen in young adults⁴⁵. Systemic inflammation and induction of Th17 cell responses were also not increased and changes to regulatory T and regulatory B cell frequencies previously reported in aged humans^{46,47} were not seen in the cyclists. However, accumulation of CD28⁻CD57⁺ T cells with a senescent/exhausted phenotype still occurred and the frequency of these cells did not differ from age-matched non-exercising adults, suggesting that lifelong physical activity ameliorates rather than totally prevents immunosenescence⁴⁵.

In a second study of healthy males aged 18-61 years (n=102) a positive correlation between aerobic fitness (**VO₂max [G]**) and the frequency of naive T cells was also reported, though this study also found reduced levels of senescent CD28⁻CD57⁺ CD4⁺ and CD8⁺ T cells in the adults in the highest tertile for VO₂max⁴⁸. Improvements in thymic output might be due to effects of physical activity on the senescent/exhausted T cell pool. Physical activity has been shown to increase apoptosis of T cells with a senescent/exhausted phenotype⁴⁹, which might increase the generation of progenitor cells⁵⁰ to maintain a richer pool of naive cells with advancing age.

The benefit of maintained thymic output and naive T cell frequency in habitual exercisers was also suggested by a study of 65-85 year old men who had undertaken a moderate or high intensity level of physical activity for an average of 25 years. These adults showed higher antibody responses to influenza vaccination than age-matched controls who were not regular exercisers⁵¹.

Taken together, these studies suggest that the emergence of certain features of immunosenescence **and the extent of immune remodelling** is likely to be heavily influenced by insufficient physical activity as humans age.

[H1] Mechanism of immune protective effect

[H2] Skeletal muscle as an immune regulatory tissue.

Skeletal muscle is now recognised as an endocrine organ, capable of expressing and secreting cytokines (referred to as myokines) into the circulation during physical activity (**Figure 2**). IL-6 was the first myokine identified. It is produced soon after the onset of physical activity, with the levels produced depending on the intensity and duration of activity⁵², reflecting muscle mass and contractile activity. IL-6 is a pro-inflammatory cytokine when it is generated via the NF- κ B signalling pathway in response to cytokines such as TNF that are produced during infection or after tissue damage. In contrast, IL-6 generated in response to exercise is anti-inflammatory, is induced via JUN N-terminal kinase (JNK) and activator protein 1 (AP1) signalling⁵³ and leads to the production of regulatory mediators (such as IL-10 and IL-1 receptor antagonist (IL-1RA)) by monocytes and macrophages⁵⁴. IL-6 also stimulates the release of cortisol from the adrenal glands, thereby providing a second anti-inflammatory signal⁵⁵. The benefit of IL-6 produced from exercising muscle was indicated in young adults in an experimental model of 'low-grade inflammation' in which the increase in plasma TNF concentration induced by low-dose administration of *E. coli* endotoxin was entirely blunted by 3h of prior ergometer cycling. These effects of physical activity were also mimicked by an infusion of IL-6, which similarly suppressed the endotoxin-induced TNF production⁵⁶. Other novel myokines released from exercising muscle have also been reported to have metabolic and immune effects. Meteorin-like is a myokine that can induce 'browning' of adipose tissue, stimulate an eosinophil-dependent increase in IL-4 and promote the polarisation of **M2-like macrophages [G]**⁵⁷. Whilst there are no data concerning net release of IL-6 or other myokines from skeletal muscle during physical activity in older people, increasing physical activity and reducing sedentary **behaviour** in older adults has been associated with lower levels of pro-inflammatory cytokines⁵⁸.

In addition to IL-6, other cytokines such as IL-7⁵⁹ and IL-15⁶⁰ are expressed and released by exercising muscle. IL-7 is required for thymocyte development⁶¹, IL-7 and IL-15 are lymphocyte proliferative factors (especially for naive T cells⁶²) and the serum levels of these cytokines declines with age⁴⁵. The potential mechanisms by which regular physical activity exerts a positive effect on thymic output and naive T cell numbers is likely to involve these myokines. In the study of older cyclists described above, these adults had higher serum levels of IL-7 and IL-15 compared with non-exercising older adults⁴⁵. IL-15 also has metabolic effects protecting against visceral adiposity by preventing lipid deposition in pre-adipocytes

and reducing white adipose tissue⁶³. As fat accumulation in the thymus is a hallmark of thymic cellular atrophy in humans⁶⁴, increased IL-15 may also protect the thymus during ageing. However, a recent study comparing IL-15 expression by adipose tissue and skeletal muscle in older adults reported that adipose tissue had higher expression of IL-15 and that serum IL-15 levels correlated with visceral fat mass but not muscle mass⁶⁵. IL-15 is also required for NK cell development and cytotoxicity and the authors suggested that fat-derived IL-15 may support NK cell-mediated immunity in older adults. However, no details of the physical activity levels in these participants were provided. In lean older adults involved in regular physical activity we would argue that muscle is a major source of IL-15. Importantly, muscle is not associated with the **adverse effects of adipose tissue, which is pro-inflammatory in nature and secretes a range of cytokines and adipokines that can contribute to inflammageing (Box 2)**.

Overall, the myokine hypothesis provides a framework that connects active skeletal muscle to the maintenance of a healthy immune system during ageing as physical inactivity, with age-related sarcopenia, both limit the immune regulatory function of muscle in old age. In addition, with the rapid progress of omics technologies, other proteins, RNA, or miRNA released from active skeletal muscle, possibly encased in exosomes, might well provide a greater understanding of this interaction with the immune system. Indeed a recent study revealed that 1 hour of cycling liberated high levels of extracellular vesicles, containing potentially novel myokines that were released into the circulation via this classical secretion independent route⁶⁶.

[H2] Effects of physical activity on innate immune cell function.

Cross-sectional studies comparing sedentary and low-fitness elders with their physically active, highly fit peers have demonstrated multiple benefits for the innate immune system in addition to the T cell population changes described above (**Figure 3**). Regular physical activity in old age is associated with enhanced NK cell function⁶⁷ and the maintenance of neutrophil bactericidal function and migratory dynamics⁶⁸. In addition, exercise interventions have been shown to lower the numbers of circulating CD16⁺ inflammatory monocytes⁶⁹, and improve neutrophil oxidative burst and phagocytosis⁷⁰. Physical activity can also lower fat mass, reducing infiltration of inflammatory monocytes to adipose tissue and increasing polarisation

of adipose tissue-resident macrophages from an M1-like pro-inflammatory to an M2-like anti-inflammatory phenotype⁷¹. This mechanism has been proposed to prevent or reverse chronic low-grade inflammation in adipose tissue that could otherwise contribute to the development of inflammaging with increased risk of age-related disease and multi-morbidity.

Physical activity and control of latent viral infection.

One other mechanism by which involvement in regular physical activity might contribute to prevention of immunosenescence, specifically age-related T cell remodelling, is through improvements in viral control. Accelerated T cell differentiation and exhaustion is partly driven by cytomegalovirus (CMV) infection, a prevalent latent herpes virus that persists for the lifetime of the host⁷². The virus is capable of periodic and subclinical reactivation, placing a significant burden on the T cell compartment. Moreover, CMV seropositivity has been linked with frailty, cognitive decline and poor immune responses to vaccines in older adults⁷³. A recent cross-sectional study in a large (n=~1400) ethnically diverse cohort aged 21-91 years revealed inverse relationships between cardiorespiratory fitness and latent viral control, with the impact of VO₂max on CMV control being more marked in those aged >65yrs¹⁸. These findings indicate that high cardiorespiratory fitness levels may protect against latent viral reactivation, which in turn will delay immunosenescence. Although the mechanisms through which physical activity can improve latent viral control remain to be determined, it is possible that each bout of physical activity causes an augmented redistribution of catecholamine-sensitive CD8⁺ T cells with viral antigen specificity and a highly differentiated phenotype and that this increases anti-viral immune surveillance and helps to lower viral loads^{74,75}. However, CMV serostatus is not always assessed in studies of physical activity and immunity and we would advocate that this must be done as it is another potential confounder in such analyses.

[H2] Catecholamines and lymphocyte β 2 adrenergic receptor signaling.

Single bouts of exercise elicit a rapid and preferential mobilisation of lymphocyte subtypes with phenotypes associated with enhanced effector function, tissue migration, catecholamine sensitivity and antigen specificity⁷⁶. NK cells are the most responsive group of lymphocytes, with even very brief physical activity causing 4-5-fold increases in peripheral

blood NK cell numbers⁷⁷. These effects of physical activity are mediated through the β 2-adrenergic receptor (β -AR) subtype⁷⁸. The mobilisation of cytotoxic lymphocyte subtypes by catecholamines following exercise provides a possible mechanism for why frequent bouts of acute dynamic physical activity can protect against cancer. Pedersen *et al.* reported that voluntary wheel running reduced tumour incidence and growth by approximately 60% across five different mouse tumour models⁷⁹. Depleting NK cells and repeating the experiments in athymic mice, which lack T cells but retain functional NK cells, confirmed that the anti-tumour effects of exercise were NK cell-mediated in mice. T cells mobilised by physical activity are more responsive to *ex vivo* stimulation with tumour antigens such as WT-1, PRAME and MAGE-A4⁸⁰. More recent work has shown that catecholamines present in plasma taken following a single exercise bout in healthy controls and in patients with breast cancer can reduce the viability of hormone-sensitive and hormone-insensitive breast cancer cell lines *in vitro* and mitigate tumour growth *in vivo* when the plasma-treated cells are transplanted into immune-compromised mice⁸¹. Taken together, these findings indicate that catecholamines released during physical activity play an important role in priming the tumour microenvironment as well as in facilitating the mobilisation and redistribution of tumour-infiltrating lymphocytes, especially myokine-sensitive NK cells.

[H2] CMV and age-related declines in NK cell β -AR sensitivity.

Ageing is the biggest risk factor for acquiring cancer and it is known that older adults mobilise fewer T cells and NK cells in response to intensity-controlled physical activity compared to their younger counterparts⁸². Furthermore, although the density of β -AR expression on lymphocytes is unaltered with ageing, β -AR sensitivity is substantially reduced⁸³. Interestingly, previous exposure to CMV markedly inhibits NK cell mobilisation in response to exercise due, in part, to a CMV-induced increase in the proportion of NK cells expressing the activating receptor NKG2C, which respond poorly to catecholamines⁸⁴. This suggests that CMV infection, and not age *per se*, is responsible for reducing the mobilisation and redistribution potential of the NK cell compartment in response to physical activity. Given that the catecholamine-dependent redistribution of NK cells appears to be a fundamental mechanism by which physical activity can inhibit cancer acquisition and progression⁷⁹, it is possible that those with

CMV might not get the same anti-tumour surveillance benefits of regular physical activity as their non-infected counterparts. Future studies investigating the effects of physical activity on NK cell catecholamine sensitivity and redistribution in the context of CMV and anti-cancer immunity are warranted.

[H2] Physical activity and gut microbiota diversity.

The intestinal microbiota plays an important role in the maintenance of host health and immunological protection. It is relatively stable throughout adult life until there is a marked reduction in biodiversity in old age⁸⁵. This altered microbiota profile includes an increase in facultative anaerobes, including *Streptococci* and *Enterobacteria* and a decline in bacteria considered to be health promoting, such as *Bifidiobacterium* and *Lactobacillus*^{86,87}. Furthermore, age-related impairment in innate immune defences (such as anti-microbial peptides, reactive oxygen species and α -defensins) favours bacterial overgrowth on epithelial surfaces and enterocytes respond by forcing an inflammatory response that drives dendritic cell-mediated differentiation of Th1 and Th17 cells⁸⁸.

A role for reduced gut microbiota diversity in immunosenescence is only now being considered, though data supporting a causative link are restricted to rodent studies. In older humans⁸⁹ and mice⁹⁰ there is an association between microbiota diversity and systemic inflammation. Theveranjan *et al.* have reported that aged germ-free (GF) mice did not display inflammaging, their macrophage bactericidal function was intact and they did not have the raised leukocyte infiltration in the lungs seen in old non-GF mice. The GF mice were also longer-lived than control littermates⁹¹. To confirm that reduced microbial diversity was responsible for the raised systemic inflammation, rather than the presence of any microbiota, two approaches were used: the study generated mice with a minimal microbiota of low microbiota diversity and still saw an increase in serum IL-6 with age. Co-housing GF mice with old but not young traditionally housed mice also raised their systemic inflammation⁹¹.

The earliest evidence for beneficial effects of physical activity on the gut microbiota came from Matsumoto and colleagues, who reported an increase in gut microbiota diversity in exercised rats⁹². There is currently a paucity of human interventional studies examining the effects of physical activity on gut microbiota, particularly in older adults. One observational

study in elite rugby players has reported an increased relative abundance of *Firmicutes* with a reduced abundance of *Bacteroides*⁹³. Allen *et al.* showed differential alterations in gut microbiota composition in lean and obese humans following a six week exercise intervention programme; specifically, they found an increased abundance of *Faecalibacterium* and *Lachnospira* with a reduced abundance of *Bacteroides* in lean participants, whereas an increased abundance of *Bacteroides* was seen in the obese participants. These changes reversed when the participants returned to their sedentary lifestyles⁹⁴. However, the relationship between physical activity, gut microbiota and mucosal immunity across the life-course remains under researched.

[H1] Physical activity as a therapy

[H2] Physical activity as an immune adjuvant.

The strongest evidence to date supporting physical activity as a powerful immune adjuvant comes from vaccination studies in older adults. Periods of extended physical activity involvement, maintained high levels of habitual physical activity in old age and single bouts of exercise prior to vaccination have all been shown to improve immune responses to the influenza and pneumococcal vaccines^{26,27,51} as well as to experimental vaccines that contain novel antigens, such as keyhole limpet haemocyanin (KLH)²⁵. The mechanism of action is likely a composite of localised inflammation and an infiltration of phagocytic and antigen-presenting cells at the site of inoculation, priming of the T cell response, increased naive T cell frequency and improvements in B cell function^{25,45,48}. Both dynamic whole-body exercise and localised resistance exercise that cause transient damage to the deltoid muscle prior to inoculation increase immune responses to the vaccine. However, more acute low-intensity exercise interventions, such as a single bout of 45 minutes brisk walking⁹⁵, or 40-minute treadmill walking at an intensity of 55%-65% of maximum heart rate⁹⁶ prior to vaccination, have so far failed to show any major or consistent improvements in vaccine responses in older adults.

As already stated, ageing remains the most significant risk factor for cancer development and there are many instances when cancer immunotherapy is less effective in the old⁹⁷; this is particularly true for responsiveness to PD1, PDL1 and CTLA4 immune

checkpoint blockade therapy, chemotherapy and tyrosine kinase inhibitors. The degree to which changes in immune phenotype and function with age contribute to cancer development is unknown, though loss of cytotoxic function of NK cells and CD8⁺ cytotoxic T cells for example would likely reduce immune surveillance capabilities in older people. In an era of precision medicine, genetic engineering and immunotherapy, simple increases in physical activity may prove to be an effective adjuvant to both limit toxicity and increase the efficacy of cancer treatments, even against the backdrop of an aged immune system (reviewed in Ref. 98). However, a challenge facing patients with cancer is that they are often too sick and frail to undertake the required level of physical activity due to the debilitating nature of their cancer treatment. To circumvent this, physical activity interventions are now being delivered before initiating treatment in a procedure referred to as 'pre-habilitation'⁹⁹. A programme that comprised both aerobic and resistance exercise lasting approximately 24 days prior to surgery for colorectal cancer significantly improved post-surgery recovery of physical function¹⁰⁰. That pre-habilitation may be effective is further suggested by the observation that higher aerobic fitness (VO₂max) levels prior to haematopoietic stem cell transplantation are inversely associated with risk of mortality and time spent in hospital¹⁰¹.

Physical activity might also help facilitate the recovery and manufacture of immune cells for immunotherapy. Single bouts of exercise increase the recovery and *ex vivo* manufacture of virus-specific T cells from virus-experienced healthy donors for the prophylactic and therapeutic treatment of post-transplant viral infections^{74,75}. Exercise has also been shown to augment the *ex vivo* manufacture of tumour-antigen-specific T cells from healthy donors in preparation for allogeneic adoptive transfer immunotherapy as a means to prevent and treat relapse after allogeneic stem cell transplantation⁸⁰. Moreover, single bouts of exercise mobilise CD34⁺ hematopoietic stem cells in to the bloodstream via the β₂-AR and may serve as an adjuvant to recover more progenitor cells from the peripheral blood of healthy granulocyte colony-stimulating factor (G-CSF) mobilized donors prior to transplantation¹⁰².

[H2] Physical activity as a therapy to prevent age-related multi-morbidity.

Advanced age is the single largest risk factor for multi-morbidity² and there is now increased evidence from animal models that interfering with core ageing processes extends lifespan but also prevents a broad range of age-related diseases¹⁰³. Whilst the current focus of this research is on pharmacological interventions to inhibit ageing processes¹⁰⁴, it is worth considering that the broad health benefits of physical activity may be mediated through an impact upon basic ageing mechanisms. Until recently, the rate of an individual's biological ageing was difficult to determine but in 2013 Horvath published an algorithm, the epigenetic clock, based on leukocyte DNA methylation at 350 CpG sites that correlated closely with chronological age and deviations from this association were indicative of increased mortality and morbidity¹⁰⁵. A few studies are now emerging that have determined associations between physical activity and this biomarker of biological age. One study of over 4500 adults revealed that physical activity had a beneficial effect on the rate of epigenetic ageing as determined by this biomarker¹⁰⁶. A smaller cross-sectional study of 248 seventy-nine year olds found no association between the epigenetic biomarker and physical activity levels measured objectively by accelerometry over 7 days¹⁰⁷, though life-long involvement in physical activity may be the more important determinant of biological ageing⁶. An analysis of the same cohort from age 70 to 76 did reveal an association between an individual's physical fitness (lung function, hand grip strength), with poorer function linked to a higher rate of change in DNA methylation¹⁰⁸.

Although ageing is a highly complex process, through research in model organisms we are now beginning to understand many of the **biological mechanisms driving ageing [G]**¹⁰⁹. These include reduced DNA damage repair, telomere shortening, reduced autophagy and compromised proteostasis, all potentially leading to induction of cell senescence. Several observational studies have shown an association between physical activity levels and telomere length, for example an analysis of data from 7813 women in the Nurse's Health Study showed a modest positive benefit of physical activity on leukocyte telomere length¹¹⁰. A 30 year longitudinal study has shown that adults who undertook moderate levels of physical activity had longer telomeres in old age than those who did either low or very high levels of activity¹¹¹, suggesting a dose-dependent effect on telomere length. Fewer researchers have carried out interventional studies to determine causality. A small 5 year study in men (n=10) with low risk prostate cancer were prescribed increased physical activity and showed longer

telomere length and higher telomerase activity compared with 25 controls with clinical surveillance only¹¹². In contrast, a 12 month randomised controlled study of aerobic exercise in 200 post-menopausal women found no evidence of an improvement in the rate of leukocyte telomere shortening¹¹³. It is possible that 12 months of increased physical activity is not sufficient to modulate telomere shortening.

Senescent cells are proliferatively quiescent but metabolically highly active and contribute to ageing in several ways, including through their secretion of pro-inflammatory cytokines (the so-called senescence-associated secretory phenotype (SASP)) thus supporting the development of inflammageing. Removal of senescent cells has been shown to prevent age-related disease and extend lifespan in mice¹⁰³. One tissue where senescent cells accumulate is adipose tissue and Schafer *et al.* have shown recently that exercise can prevent accumulation of these cells in diet-induced obesity in mice¹¹⁴. Physical activity is also able to increase autophagy, including in muscle¹¹⁵, which will have benefits for metabolism and proteostasis.

Physical activity may thus be able to counteract mechanisms associated with ageing including modulating telomere shortening, cell senescence, autophagy, inflammation and epigenetic changes and thereby ameliorate the ageing phenotype including the multi-morbidity of old age. As immune cells from older adults also demonstrate the presence of these ageing mechanisms, including telomere shortening¹¹⁶, reduced autophagy¹¹⁷, a pro-inflammatory phenotype^{38,39} and epigenetic changes associated with biological age¹⁰⁵, physical activity may also mediate its beneficial effects on immunity by counteracting these core processes.

[H1] Conclusions

Hippocrates in 400 BC claimed that “Walking is man’s best medicine” and it is clear that physical activity has broad impacts upon health across the life course, many mediated through improved immunity and reduced systemic inflammation¹². Maintaining a high level of physical activity across the lifespan is arguably the blueprint passed down from our evolutionary heritage and can ameliorate most of the typical aged phenotype, including immunosenescence^{44,45,98}. To firm up the case for a causative link between physical activity,

immunosenescence and health much more interventional studies in humans are required. The link between immunosenescence and disease also requires further evidence to show reduced morbidity when immune ageing is selectively targeted. To date this has only been achieved following short-term treatment with rapamycin analogues to inhibit mammalian target of rapamycin (mTOR), which was shown to improve responses to influenza vaccines in older adults and reduce influenza-like infections¹¹⁸. If physical activity interventions can then be shown to modulate the immune system through the same mechanisms (for example, through inhibition of mTOR), this will help to provide support for the direct benefits of physical activity for ameliorating immunosenescence. Furthermore, the current literature reports that physical activity is useful as an adjuvant to immunotherapies such as vaccination and immune cell therapy. It is important going forward to stratify physical activity prescription for dose and intensity and to determine in which age-related diseases it will be effective.

Box 1: Definitions of physical activity and exercise

The US Centers for Disease Control and Prevention defines physical activity as “Any bodily movement produced by the contraction of skeletal muscle that increases energy expenditure above a basal level. Physical activity generally refers to the subset of physical activity that enhances health.” Exercise is defined as “A subcategory of physical activity that is planned, structured, repetitive, and purposive in the sense that the improvement or maintenance of one or more components of physical fitness is the objective.”

Box 2: Adipose tissue and inflammaging

Adipose tissue produces a range of pro-inflammatory cytokines, termed adipokines. In addition, adipose tissue contains macrophages and senescent cells that contribute to the pro-inflammatory output. The increase in adiposity with age thus contributes to inflammaging and in turn to age-related disease.

Figure 1. The evolution of increased longevity

Our nearest primate relatives such as chimpanzees and gorillas live for approximately 10-15 years in the wild once they reach maturity. 5 million years of evolution resulted in a doubling of life expectancy in the hunter-gatherer tribes such as the Ache and Hiwi and this lifespan persisted into the modern 18th century humans. Just 250 years later, as a result of improved sanitation and health care, life expectancy has doubled again⁴ and our modern more sedentary lifestyle is thus maladjusted to our genetic inheritance with consequences for health in old age.

Figure 2. Muscle as an immune regulatory organ

In the absence of infection skeletal muscle is a major source of cytokines, termed myokines. Active muscle produces a range of myokines including IL-6 which has anti-inflammatory actions via the induction of IL-10 and IL-1RA by monocyte/macrophages. Muscle derived IL-15 has a range of actions including promoting the survival on naïve T cells, enhancing NK cell production and cytotoxicity and influencing fat deposition by inhibition on lipogenesis. IL-7 has thymoprotective actions helping to maintain thymic output. Skeletal muscle also produces a range of growth factors, including IGF-1 and Meteorin-like (MTRNL) which promote conversion of white to brown adipose tissue, increases IL-4 secretion and

macrophage M2 polarisation. Increased physical activity leads to reduced intermuscular adipose tissue, which is a source of the inhibitory muscle growth factor myostatin.

Figure 3. Physical activity as an immune adjuvant

Maintaining a physically active lifestyle prevents age-related declines in lymphocyte β_2 -adrenergic receptor (β_2 -AR) sensitivity, allowing for the catecholamine-mediated redistribution of NK cells and viral-specific T cells (VSTs) between the blood and tissues with each bout of physical activity. Lymphocytes and monocytes mobilised in to the blood with physical activity can potentially be collected for immune cell therapeutics (e.g. allogeneic adoptive transfer immunotherapy). The frequent redistribution of NK cells and VSTs with each exercise bout increases immune surveillance, reducing the frequency of latent viral reactivation. This in turn reduces the antigenic load placed on the T cell compartment and prevents the accumulation of senescent/exhausted T cells whilst also maintaining the number and diversity of peripheral naïve T cells. Physical activity can also increase apoptosis of senescent/exhausted T cells which increases the production of hematopoietic progenitor cells. Maintaining a diverse pool of naïve T-cells with physical activity with advancing age will reduce infection risk and increase protection provided from vaccines.

Table 1. Changes to immune cell numbers, phenotype and function with age.

Cell type or tissue	Effects of ageing on cell numbers and phenotype	Effects of ageing on cell functions	References
Neutrophil	Increased numbers	Decreased chemotactic accuracy; decreased bactericidal properties (e.g. phagocytosis , ROS and NET generation)	119,120
Monocyte	Increased total numbers; increased proportions of CD14 ⁺ 16 ⁺⁺ non-classical monocytes; decreased proportions of CD14 ⁺ 16 ⁻ classical monocytes; equivalent levels of TLR2, TLR4, TLR5 expression	Decreased phagocytosis, efferocytosis, ROS generation; increased basal production of pro- inflammatory cytokines; decreased cytokine production in response to LPS, TLR1/TLR2 or TLR7 stimulation; equivalent cytokine production following TLR2/TLR6, TLR4, and TLR5 stimulation	121,122
NK cell and NKT cells	Increased total NK cell and NKT cell numbers; decreased invariant NKT cell numbers; increased proportions of CD56 ^{Dim} NK cells; decreased expression of CD94, KLRG1, NKp46 expression on NK cells	Reduced NK cell-mediated cytotoxicity at the single-cell level; reduced perforin release; equivalent levels of NK cell-mediated antibody-dependent cell cytotoxicity	123,124
Dendritic cell	Decreased or equivalent numbers of plasmacytoid DCs and myeloid DCs;	Reduced phagocytosis; reduced recruitment to lymphoid organs; reduced induction of T	125,126

	Equivalent levels of MHC II, CD11c and CD123 expression; equivalent levels of TLR7 and TLR9 expression	cell proliferation , IFN γ and IL-12 secretion	
Thymus	Decreased stromal cell and thymocyte cellularity; decreased numbers of double-positive thymocytes; increased adipocyte infiltration; decreased levels of thymus-enhancing cytokines (e.g. IL-7 and KGF); increased levels of thymus-suppressive cytokines (e.g IL6 and TNF)	Decreased naïve T cell output; decreased numbers of recent thymic emigrants	127,128
T cell	Decreased CD3+ T cell numbers; decreased proportions of naïve T cells, increased proportions of memory T cells; increased proportions of T cells with senescent/exhausted phenotype (CD28 ^{-ve} , CD57 ^{+ve} ,KLRG1 ^{+ve} , PD1 ^{+ve}); increased proportions of regulatory T cells	Decreased T cell proliferation; increased secretion of pro-inflammatory cytokines; decreased CD4+ helper T cell activity; decreased CD8+ T cell cytotoxicity; increased Th17 cell polarisation	38, 46, 129, 130
Bone marrow	Decreased numbers of pre-B cells; fewer niches for B cell development	Reduced expression of transcription factors crucial for B cell differentiation (e.g. E47); reduced secretion of IL-17 by stromal cells; decreased B cell lymphopoiesis	131,132
B cell	Decreased total B cell numbers; decreased proportions of naïve B cells and regulatory B cells, increased	Reduced antibody production, clonal diversity and lower antibody affinity; lower IL-10 secretion by regulatory B cells	39,47

	proportions of memory B cells		
--	-------------------------------	--	--

Abbreviations: ROS, Reactive oxygen species; NET, neutrophil extracellular trap; TLR, Toll-like receptor; LPS, lipopolysaccharide; TNF, tumour-necrosis factor; KLRG1, killer cell lectin-like receptor subfamily G member 1; NKp46, natural killer cell p46-related protein; KGF, keratinocyte growth factor;

Acknowledgments

The authors would like to thank Dr Martin Whitham and Dr Ann Skulas-Ray for their careful reading of the manuscript.

Author contributions

J.M.L., N.A.D., S.D.R.H., R.J.S. and G.N. were involved in researching data, discussion of content and in the writing, review and editing of the manuscript.

Competing interests

The authors declare no competing interests.

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Reviewer information

Nature Reviews Immunology thanks M. Phillips, K. Timmerman and J. Turner for their contribution to the peer review of this work.

References

- 1 Kirkwood, T. B. L. Why and how are we living longer? *Exp. Physiol.* 102, 1067-1074 (2017).
- 2 Salomon, J. A., et al. Healthy life expectancy for 187 countries, 1990-2010: a systematic analysis for the Global Burden Disease Study 2010. *Lancet* 380, 2144-2162 (2012).
- 3 Rocca, W. A., et al. Prevalence of multimorbidity in a geographically defined American population: patterns by age, sex, and race/ethnicity. *Mayo Clin. Proc.* 89, 1336-1349 (2014).
- 4 Colchero, F., et al. The emergence of longevous populations. *Proc. Natl. Acad. Sci. USA* 113, E7681-E7690 (2016).
- 5 Booth, F. W., Chakravarthy, M. V. & Spangenburg, E. E. Exercise and gene expression: physiological regulation of the human genome through physical activity. *J. Physiol.* 543, 399-411 (2002).
- 6 Harridge, S. D. & Lazarus, N. R. Physical activity, aging, and physiological function. *Physiology (Bethesda)* 32, 152-161 (2017).
- 7 Gopinath, B., Kifley, A., Flood, V. M. & Mitchell, P. Physical activity as a determinant of successful aging over ten years. *Sci. Rep.* 8, 10522 (2018).
- 8 Harber, M. P., et al. Impact of cardiorespiratory fitness on all-cause and disease-specific mortality: Advances since 2009. *Prog. Cardiovasc. Dis.* 60, 11-20 (2017).
- 9 Barry, V. W., et al. Fitness vs. fatness on all-cause mortality: a meta-analysis. *Prog. Cardiovasc. Dis.* 56, 382-390 (2014).
- 10 Bouchard, C., Blair, S. N. & Katzmarzyk, P. T. Less sitting, more physical activity, or higher fitness? *Mayo Clin. Proc.* 90, 1533-1540 (2015).
This paper reviews the evidence for physical activity level and sedentary time as independent variables influencing health, proposing there should be recommendations made for both.
- 11 Cabanas-Sanchez, V., et al. Physical activity, sitting time, and mortality from inflammatory diseases in older adults. *Front. Physiol.* 9, 898 (2018).
- 12 Gleeson, M., et al. The anti-inflammatory effects of exercise: mechanisms and implications for the prevention and treatment of disease. *Nat. Rev. Immunol.* 11, 607-615 (2011).
- 13 Dhalwani, N. N., et al. Long terms trends of multimorbidity and association with physical activity in older English population. *Int. J. Behav. Nutr. Phys. Act.* 13, 8 (2016).
This longitudinal study describes population level data suggesting an inverse association between physical activity level and multimorbidity in older adults.
- 14 Vancampfort, D., et al. Chronic physical conditions, multimorbidity and physical activity across 46 low- and middle-income countries. *Int. J. Behav. Nutr. Phys. Act.* 14, 6 (2017).
- 15 Andersen, Z. J., et al. A study of the combined effects of physical activity and air pollution on mortality in elderly urban residents: the Danish Diet, Cancer, and Health Cohort. *Environ. Health Perspect.* 123, 557-563 (2015).
- 16 Pape, K., et al. Leisure-time physical activity and the risk of suspected bacterial infections. *Med. Sci. Sports Exerc.* 48, 1737-1744 (2016).
- 17 Baik, I., et al. A prospective study of age and lifestyle factors in relation to community-acquired pneumonia in US men and women. *Arch. Intern. Med.* 160, 3082-3088 (2000).
- 18 Simpson, R. J., et al. Cardiorespiratory fitness is associated with better control of latent herpesvirus infections in a large ethnically diverse community sample:

Evidence from the Texas City Stress and Health Study. *Brain Behav. Immun.* 66, e35 (2017).

This paper suggests that involvement in regular physical activity improves anti-viral immunity to prevalent latent viral infections such as CMV, which are thought to be one driver of immunosenescence.

- 19 Leitzmann, M., et al. European Code against Cancer 4th Edition: Physical activity and cancer. *Cancer Epidemiol.* 39 Suppl. 1, S46-555 (2015).
- 20 Higuera-Fresnillo, S., et al. Physical activity and association between frailty and all-cause and cardiovascular mortality in older adults: Population-based prospective cohort study. *J. Am. Geriatr. Soc.* 66, 2097-2103 (2018).
- 21 Morris, J. K., et al. Aerobic exercise for Alzheimer's disease: A randomized controlled pilot trial. *PLoS One* 12, e0170547 (2017).
- 22 Lowder, T., Padgett, D. A. & Woods, J. A. Moderate exercise protects mice from death due to influenza virus. *Brain Behav. Immun.* 19, 377-380 (2005).
- 23 Lowder, T., Padgett, D. A. & Woods, J. A. Moderate exercise early after influenza virus infection reduces the Th1 inflammatory response in lungs of mice. *Exerc. Immunol. Rev.* 12, 97-111 (2006).
- 24 Andrew, M. K., et al. The importance of frailty in the assessment of influenza vaccine effectiveness against influenza-related hospitalization in elderly people. *J. Infect. Dis.* 216, 405-414 (2017).
- 25 Pascoe, A. R., Fiatarone Singh, M. A. & Edwards, K. M. The effects of exercise on vaccination responses: a review of chronic and acute exercise interventions in humans. *Brain Behav. Immun.* 39, 33-41 (2014).
- 26 Woods, J. A., et al. Cardiovascular exercise training extends influenza vaccine seroprotection in sedentary older adults: the immune function intervention trial. *J. Am. Geriatr. Soc.* 57, 2183-2191 (2009).
- 27 Kohut, M. L., et al. Moderate exercise improves antibody response to influenza immunization in older adults. *Vaccine* 22, 2298-2306 (2004).

One of the first papers to show that an extended period of increased physical activity increases vaccine responses in older adults.

- 28 Metsios, G. S., et al. Individualised exercise improves endothelial function in patients with rheumatoid arthritis. *Ann. Rheum. Dis.* 73, 748-751 (2014).
- 29 Manning, V. L., et al. Education, self-management, and upper extremity exercise training in people with rheumatoid arthritis: a randomized controlled trial. *Arthritis Care Res.* 66, 217-227 (2014).
- 30 McLean, H. Q., et al. Influenza vaccine effectiveness in the United States during 2012-2013: variable protection by age and virus type. *J. Infect. Dis.* 211, 1529-1540 (2015).
- 31 Foxman, B. Urinary tract infection syndromes: occurrence, recurrence, bacteriology, risk factors, and disease burden. *Infect. Dis. Clin. North Am.* 28, 1-13 (2014).
- 32 Kawai, K., Gebremeskel, B. G. & Acosta, C. J. Systematic review of incidence and complications of herpes zoster: towards a global perspective. *BMJ Open* 4, e004833 (2014).
- 33 Trintinaglia, L., et al. Features of immunosenescence in women newly diagnosed with breast cancer. *Front. Immunol.* 9, 1651 (2018).
- 34 Franceschi, C. & Campisi, J. Chronic inflammation (inflammaging) and its potential contribution to age-associated diseases. *J. Gerontol. A Biol. Sci. Med. Sci.* 69 Suppl. 1, S4-9 (2014).

An update on the evidence suggesting that the age-related increase in systemic inflammation is a contributor to diseases of old age.

- 35 Fuggle, N. R., et al. Relationships between markers of inflammation and bone density: findings from the Hertfordshire Cohort Study. *Osteoporos. Int.* 29, 1581-1589 (2018).
- 36 Turner, J. E. Is immunosenescence influenced by our lifetime "dose" of exercise? *Biogerontol.* 17, 581-602 (2016)
- 37 Flynn, M.G., Markofski, M.M. & Carrillo, A.E. Elevated inflammatory status and increased risk of chronic disease in chronological aging – Inflammaging or Inflamm-inactivity? *Aging Dis.* 10, 147-156 (2019).
- 38 Callender, L.A., et al. Human CD8+ EMRA T cells display a senescence-associated secretory phenotype regulated by p38 MAPK. *Aging Cell* 17, e12675 (2018).
Together with reference 39 this paper shows that highly differentiated lymphocytes show the same pro-inflammatory secretory phenotype seen in non-immune cells and may thus contribute to inflammaging.
- 39 Frasca, D., Diaz, A., Romero, M. & Blomberg, B. B. Human peripheral late/exhausted memory B cells express a senescent-associated secretory phenotype and preferentially utilize metabolic signaling pathways. *Exp. Gerontol.* 87, 113-120 (2017).
- 40 Martinez de Toda, I., et al. Immune function parameters as markers of biological age and predictors of longevity. *Aging* 8, 3110-3119 (2016).
- 41 Alpert, A., et al. High resolution longitudinal immune profiling reveals a clinically meaningful Metric 2 from dynamics of healthy immune-aging towards an older adult homeostasis. *Nature Med.* In press (2019).
- 42 Koetz, K., et al. T cell homeostasis in patients with rheumatoid arthritis. *Proc. Natl. Acad. Sci. USA* 97, 9203-9208 (2000).
- 43 Thewissen, M., et al. Analyses of immunosenescent markers in patients with autoimmune disease. *Clin. Immunol.* 123, 209-218 (2007).
- 44 Pollock, R. D., et al. An investigation into the relationship between age and physiological function in highly active older adults. *J. Physiol.* 593, 657-680 (2015).
This study assessed a group of highly active older adults and revealed that many classic features of physiological ageing, such as sarcopenia, were ameliorated by maintained physical activity.
- 45 Duggal, N. A., Pollock, R. D., Lazarus, N. R., Harridge, S. & Lord, J. M. Major features of immunosenescence, including reduced thymic output, are ameliorated by high levels of physical activity in adulthood. *Aging Cell* 17, 12750 (2018).
This paper, based on the same cohort as in reference 44, revealed that many but not all features of immunosenescence were prevented by maintained physical activity.
- 46 Pereira, B.I. & Akbar, A.N. Convergence of innate and adaptive immunity during human aging. *Front. Immunol.* 7, 445 (2016).
- 47 Duggal, N. A., Upton, J., Phillips, A. C., Sapey, E. & Lord, J. M. An age-related numerical and functional deficit in CD19(+) CD24(hi) CD38(hi) B cells is associated with an increase in systemic autoimmunity. *Aging Cell* 12, 873-881 (2013).
- 48 Spielmann, G., et al. Aerobic fitness is associated with lower proportions of senescent blood T-cells in man. *Brain Behav. Immun.* 25, 1521-1529 (2011).
- 49 Kruger, K., et al. Apoptosis of T-cell subsets after acute high-intensity interval exercise. *Med. Sci. Sports Exer.* 48, 2021-2029 (2016).
- 50 Mooren, F. C. & Kruger, K. Apoptotic lymphocytes induce progenitor cell mobilization after exercise. *J. Applied Physiol.* 119, 135-139 (2015).
- 51 de Araujo, A. L., et al. Elderly men with moderate and intense training lifestyle present sustained higher antibody responses to influenza vaccine. *Age* 37, 105 (2015).

This paper reports that maintained physical activity in to old age results in increased functional immunity, namely improved vaccine responses.

- 52 Pedersen, B. K. & Febbraio, M. A. Muscles, exercise and obesity: skeletal muscle as a secretory organ. *Nat. Rev. Endocrinol.* 8, 457-465 (2012).
- 53 Whitham, M., et al. Contraction-induced interleukin-6 gene transcription in skeletal muscle is regulated by c-Jun terminal kinase/activator protein-1. *J. Biol. Chem.* 287, 10771-10779 (2012).
- 54 Munoz-Canoves, P., Scheele, C., Pedersen, B. K. & Serrano, A. L. Interleukin-6 myokine signaling in skeletal muscle: a double-edged sword? *FEBS J.* 280, 4131-4148 (2013).
- 55 Bethin, K. E., Vogt, S. K. & Muglia, L. J. Interleukin-6 is an essential, corticotropin-releasing hormone-independent stimulator of the adrenal axis during immune system activation. *Proc. Natl. Acad. Sci. USA* 97, 9317-9322 (2000).
- 56 Starkie, R., Ostrowski, S. R., Jauffred, S., Febbraio, M. & Pedersen, B. K. Exercise and IL-6 infusion inhibit endotoxin-induced TNF-alpha production in humans. *FASEB J.* 17, 884-886 (2003).
- 57 Rao, R. R., et al. Meteorin-like is a hormone that regulates immune-adipose interactions to increase beige fat thermogenesis. *Cell* 157, 1279-1291 (2014).
- 58 Nilsson, A., Bergens, O. & Kadi, F. Physical activity alters inflammation in older adults by different intensity levels. *Med. Sci. Sports Exerc.* 50, 1502-1507 (2018).
- 59 Haugen, F., et al. IL-7 is expressed and secreted by human skeletal muscle cells. *Am. J. Physiol. Cell Physiol.* 298, C807-816 (2010).

Together with reference 60 this paper shows how active skeletal muscle could support the function, survival and proliferation of immune cells through IL7 and IL15 production.

- 60 Rinnov, A., et al. Endurance training enhances skeletal muscle interleukin-15 in human male subjects. *Endocrine* 45, 271-278 (2014).
- 61 Shitara, S., et al. IL-7 produced by thymic epithelial cells plays a major role in the development of thymocytes and TCRgammadelta+ intraepithelial lymphocytes. *J. Immunol.* 190, 6173-6179 (2013).
- 62 Wallace, D. L., et al. Prolonged exposure of naive CD8+ T cells to interleukin-7 or interleukin-15 stimulates proliferation without differentiation or loss of telomere length. *Immunol* 119, 243-253 (2006).
- 63 Nielsen, A. R., et al. Association between interleukin-15 and obesity: interleukin-15 as a potential regulator of fat mass. *J. Clin. Endocrinol. Metab.* 93, 4486-4493 (2008).
- 64 Yang, H., Youm, Y. H. & Dixit, V. D. Inhibition of thymic adipogenesis by caloric restriction is coupled with reduction in age-related thymic involution. *J. Immunol.* 183, 3040-3052 (2009).
- 65 Al-Attar, A., et al. Human body composition and immunity: Visceral adipose tissue produces IL-15 and muscle strength inversely correlates with NK Cell function in elderly humans. *Front. Immunol.* 9, 440 (2018).
- 66 Whitham, M., et al. Extracellular vesicles provide a means for tissue crosstalk during exercise. *Cell Metab.* 27, 237-251 (2018).

This paper shows that the endocrine role of skeletal muscle may be mediated through the release of exosomes.

- 67 Nieman, D. C., et al. Physical activity and immune function in elderly women. *Med. Sci. Sports. Exerc.* 25, 823-831 (1993).
- 68 Bartlett, D. B., et al. Habitual physical activity is associated with the maintenance of neutrophil migratory dynamics in healthy older adults. *Brain Behav. Immun.* 56, 12-20 (2016).

- 69 Timmerman, K. L., Flynn, M. G., Coen, P. M., Markofski, M. M. & Pence, B. D. Exercise training-induced lowering of inflammatory (CD14+CD16+) monocytes: a role in the anti-inflammatory influence of exercise? *J. Leukoc. Biol.* 84, 1271-1278 (2008).
- 70 Bartlett, D. B., et al. Ten weeks of high-intensity interval walk training is associated with reduced disease activity and improved innate immune function in older adults with rheumatoid arthritis: a pilot study. *Arthritis Res. Ther.* 20, 127 (2018).
- 71 Auerbach, P., et al. Differential effects of endurance training and weight loss on plasma adiponectin multimers and adipose tissue macrophages, in younger moderately overweight men. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 305, R490-498 (2013).
- 72 Nikolich-Zugich, J. & van Lier, R. A. W. Cytomegalovirus (CMV) research in immune senescence comes of age: overview of the 6th International Workshop on CMV and Immunosenescence. *Geroscience* 39, 245-249 (2017).
- 73 Griffiths, P. D. & Mahungu, T. Why CMV is a candidate for elimination and then eradication. *J. Virus Erad.* 2, 131-135 (2016).
- 74 Kunz, H. E., et al. A single exercise bout augments adenovirus-specific T-cell mobilization and function. *Physiol. Behav.* 194, 56-65 (2018).
- 75 Spielmann, G., Bollard, C. M., Kunz, H., Hanley, P. J. & Simpson, R. J. A single exercise bout enhances the manufacture of viral-specific T-cells from healthy donors: implications for allogeneic adoptive transfer immunotherapy. *Sci. Rep.* 6, 25852 (2016).
- 76 Simpson, R. J., Bigley, A. B., Agha, N., Hanley, P. J. & Bollard, C. M. Mobilizing immune cells with exercise for cancer immunotherapy. *Exerc. Sports Sci. Rev.* 45, 163-172 (2017).
- 77 Rooney, B. V., et al. Lymphocytes and monocytes egress peripheral blood within minutes after cessation of steady state exercise: A detailed temporal analysis of leukocyte extravasation. *Physiol. Behav.* 194, 260-267 (2018).
- 78 Graff, R. M., et al. beta(2)-Adrenergic receptor signaling mediates the preferential mobilization of differentiated subsets of CD8+ T-cells, NK-cells and non-classical monocytes in response to acute exercise in humans. *Brain Behav. Immun.* 74, 143-153 (2018).
- 79 Pedersen, L., et al. Voluntary running suppresses tumor growth through epinephrine- and IL-6-dependent NK cell mobilization and redistribution. *Cell Metab.* 23, 554-562 (2016).
- 80 LaVoy, E. C., et al. A single bout of dynamic exercise enhances the expansion of MAGE-A4 and PRAME-specific cytotoxic T-cells from healthy adults. *Exerc. Immunol. Rev.* 21, 144-153 (2015).
- 81 Dethlefsen, C., et al. Exercise-induced catecholamines activate the Hippo tumor suppressor pathway to reduce risks of breast cancer development. *Cancer Res.* 77, 4894-4904 (2017).
- 82 Spielmann, G., et al. The effects of age and latent cytomegalovirus infection on the redeployment of CD8+ T cell subsets in response to acute exercise in humans. *Brain Behav. Immun.* 39, 142-151 (2014).
- 83 O'Hara, N., Daul, A. E., Fesel, R., Siekmann, U. & Brodde, O. E. Different mechanisms underlying reduced beta 2-adrenoceptor responsiveness in lymphocytes from neonates and old subjects. *Mech. Ageing Dev.* 31, 115-122 (1985).
- 84 Bigley, A. B., Spielmann, G., Agha, N. & Simpson, R. J. The effects of age and latent cytomegalovirus infection on NK-Cell phenotype and exercise responsiveness in man. *Oxid. Med. Cell Longev.* 2015, 979645 (2015).

- 85 O'Toole, P. W. & Jeffery, I. B. Gut microbiota and aging. *Science* 350, 1214-1215 (2015).
- 86 An, R., et al. Age-dependent changes in GI physiology and microbiota: time to reconsider? *Gut* 67, 2213-2222 (2018).
- 87 Biagi, E., et al. Gut Microbiota and Extreme Longevity. *Curr. Biol.* 26, 1480-1485 (2016).
- 88 Biagi, E., et al. Ageing and gut microbes: perspectives for health maintenance and longevity. *Pharmacol. Res.* 69, 11-20 (2013).
- 89 Claesson, M.J., et al. Gut microbiota composition correlates with diet and health in the elderly. *Nature* 488, 178-184 (2012).
- 90 Conley, M.N., et al. Aging and serum MCP-1 are associated with gut microbiome composition in a murine model. *PeerJ* 4, e1854 (2016).
- 91 Thevaranjan, N., et al. Age-associated microbial dysbiosis promotes intestinal permeability, systemic inflammation and macrophage dysfunction. *Cell Host Microbe* 21, 455-466 (2017).
- 92 Matsumoto, M., et al. Voluntary running exercise alters microbiota composition and increases n-butyrate concentration in the rat cecum. *Biosci. Biotechnol. Biochem.* 72, 572-576 (2008).
- 93 Clarke, S. F., et al. Exercise and associated dietary extremes impact on gut microbial diversity. *Gut* 63, 1913-1920 (2014).
- 94 Allen, J. M., et al. Exercise alters gut microbiota composition and function in lean and obese humans. *Med. Sci. Sports Exerc.* 50, 747-757 (2018).
- 95 Long, J. E., et al. Vaccination response following aerobic exercise: can a brisk walk enhance antibody response to pneumococcal and influenza vaccinations? *Brain Behav. Immun.* 26, 680-687 (2012).
- 96 Ranadive, S. M., et al. Effect of acute aerobic exercise on vaccine efficacy in older adults. *Med. Sci. Sports Exerc.* 46, 455-461 (2014).
- 97 Poropatich, K., Fontanarosa, J., Samant, S., Sosman, J. A. & Zhang, B. Cancer immunotherapies: Are they as effective in the elderly? *Drugs Aging* 34, 567-581 (2017).
- 98 Turner, J.E. & Brum, P.C. Does regular exercise counter T cell immunosenescence countering the risk of developing cancer and promoting successful treatment of malignancies? *Oxid. Med. Cell Longev.* 4234765 (2017).
- 99 Minnella, E. M., et al. Effect of exercise and nutrition prehabilitation on functional capacity in esophagogastric cancer surgery: A randomized clinical trial. *JAMA Surg.* 153, 1081-1089 (2018).
- 100 Gillis, C., et al. Prehabilitation versus rehabilitation: a randomized control trial in patients undergoing colorectal resection for cancer. *Anesthesiol.* 121, 937-947 (2014).
- 101 Wood, W. A., et al. Cardiopulmonary fitness in patients undergoing hematopoietic SCT: a pilot study. *Bone Marrow Transplant* 48, 1342-1349 (2013).
- 102 Agha, N. H., et al. Vigorous exercise mobilizes CD34+ hematopoietic stem cells to peripheral blood via the beta2-adrenergic receptor. *Brain Behav. Immun.* 68, 66-75 (2018).
- 103 Baker, D. J., et al. Clearance of p16Ink4a-positive senescent cells delays ageing-associated disorders. *Nature* 479, 232-236 (2011).
- The paper describes a progeroid mouse engineered to delete senescent cells as they arise, providing the first evidence that accumulation of senescent cells with age is a driver of ageing and age-related disease.**
- 104 Kirkland, J. L., Tchkonja, T., Zhu, Y., Niedernhofer, L. J. & Robbins, P. D. The clinical potential of senolytic drugs. *J. Am. Geriatr. Soc.* 65, 2297-2301 (2017).

- 105 Horvath, S. DNA methylation age of human tissues and cell types. *Genome Biol.* 14, R115 (2013).
- 106 Quach, A., et al. Epigenetic clock analysis of diet, exercise, education, and lifestyle factors. *Aging* 9, 419-446 (2017).
- 107 Gale, C. R., et al. The epigenetic clock and objectively measured sedentary and walking behavior in older adults: the Lothian Birth Cohort 1936. *Clin. Epigenetics* 10, 4 (2018).
- 108 Marioni, R. E., et al. The epigenetic clock is correlated with physical and cognitive fitness in the Lothian Birth Cohort 1936. *Int. J. Epidemiol.* 44, 1388-1396 (2015).
- 109 Lopez-Otin, C., Blasco, M. A., Partridge, L., Serrano, M. & Kroemer, G. The hallmarks of aging. *Cell* 153, 1194-1217 (2013).
- 110 Du, M., et al. Physical activity, sedentary behavior and leukocyte telomere length in women. *Am. J. Epidemiol.* 175, 414-422 (2012).
- 111 Denham, J., O'Brien, B. J. & Charchar, F. J. Telomere length maintenance and cardio-metabolic disease prevention through exercise training. *Sports Med.* 46, 1213-1237 (2016).
- 112 Ornish, D., et al. Effect of comprehensive lifestyle changes on telomerase activity and telomere length in men with biopsy-proven low-risk prostate cancer: 5-year follow-up of a descriptive pilot study. *Lancet Oncol.* 14, 1112-1120 (2013).
- 113 Friedenreich, C. M., *et al.* Effect of a 12-month exercise intervention on leukocyte telomere length: Results from the ALPHA Trial. *Cancer Epidemiol.* 56, 67-74 (2018).
- 114 Schafer, M. J., et al. Exercise Prevents Diet-Induced Cellular Senescence in Adipose Tissue. *Diabetes* 65, 1606-1615 (2016).
- 115 He, C., et al. Exercise-induced BCL2-regulated autophagy is required for muscle glucose homeostasis. *Nature* 481, 511-515 (2012).
- 116 Akbar, A.N. & Fletcher, J.M. Memory T cell homeostasis and senescence during aging. *Curr. Opin. Immunol.* 17, 480-485 (2005).
- 117 Zhang, H., Puleston, D.J. & Simon, A.K. Autophagy in immune senescence. *Trends Mol. Med.* 22, 671-686 (2016).
- 118 Mannick, J.B., et al. TORC1 inhibition enhances immune function and reduces infections in the elderly. *Sci. Transl. Med.* 10, eaaq1564 (2018).
- The first report of the use of drugs, rapamycin analogues, that target a core ageing process and improve functional immunity in older adults.**
- 119 Drew, W., et al. Inflammation and neutrophil immunosenescence in health and disease: Targeted treatment to improve clinical outcomes in the elderly. *Exp. Gerontol.* 105, 70-77 (2018).
- 120 Sapey, E., et al. Phosphoinositide 3 kinase inhibition restores neutrophil accuracy in the elderly: towards targeted treatments for immunosenescence. *Blood* 123, 239-248 (2014).
- 121 Qian, F., et al. Age-associated elevation in TLR5 leads to increased inflammatory responses in the elderly. *Aging Cell* 11, 104-110 (2012).
- 122 Hearps, A.C., et al. Aging is associated with chronic innate immune activation and dysregulation of monocyte phenotype and function. *Aging Cell* 11, 867-875 (2012).
- 123 Hazeldine, J., et al. Reduced release and binding of perforin at the immunological synapse underlies the age-related decline in natural killer cell cytotoxicity. *Aging Cell* 11, 751-759 (2012).
- 124 Peralbo, E., et al. Invariant NKT and NKT-like lymphocytes: two different T cell subsets that are differentially affected by ageing. *Exp. Gerontol.* 42, 703-708 (2007).
- 125 Agrawal, A., et al. Role of dendritic cells in inflammation and loss of tolerance in the elderly. *Front. Immunol.* 26, 8:896 (2017).

- 126 Chougnnet, C. A., et al. Loss of phagocytic and antigen cross-presenting capacity in aging dendritic cells is associated with mitochondrial dysfunction. *J. Immunol.* 195, 2624-2632 (2015).
- 127 Majumdar, S., et al. Thymic Atrophy: Experimental studies and therapeutic interventions. *Scand. J. Immunol.* 87, 4-14 (2018).
- 128 Ventevogel, M.S. & Sempowski, G.D. Thymic rejuvenation and aging. *Curr. Opin. Immunol.* 25, 516-522 (2013).
- 129 Jergović, M., et al. Intrinsic and extrinsic contributors to defective CD8+ T cell responses with aging. *Exp. Gerontol.* 105, 140-145 (2018).
- 130 Jagger, A., Shimojima, Y., Goronzy, J. J. & Weyand, C. M. Regulatory T cells and the immune aging process: a mini-review. *Gerontol.* 60, 130-137 (2014).
- 131 Cancro, M.P., et al. B cells and aging: molecules and mechanisms. *Trends Immunol.* 30, 313-318 (2009).
- 132 Kogut, I., et al. B cell maintenance and function in aging. *Semin. Immunol.* 24, 342-349 (2012).

Glossary terms

Healthy life expectancy.

Life expectancy is the predicted total number of years an individual is likely to live and the proportion of life that will be spent in good health is termed healthy life expectancy or healthspan.

Sarcopenia.

Sarcopenia refers to a condition of low muscle mass and function (strength) and commonly occurs with age or chronic illness. The European Working Group on Sarcopenia in Older People has defined low muscle mass as >2 standard deviations from the mean value for young adults and low strength as a walking speed of less than 0.8m/s and hand grip strength of <30 kg in males, <20 kg in females.

M1 and M2-like macrophages.

'M1' and 'M2' are classifications historically used to define macrophages activated *in vitro* as pro-inflammatory (when 'classically' activated with IFN and LPS) or anti-inflammatory (when 'alternatively' activated with IL-4 or IL-10), respectively. However, *in vivo* macrophages are highly specialized, transcriptomically dynamic and extremely heterogeneous with regards to their phenotypes and functions, which are continuously shaped by their tissue microenvironment. Therefore, the M1 or M2 classification is too simplistic to explain the true nature of *in vivo* macrophages, although these terms are still often used to indicate whether the macrophages in question are more pro- or anti-inflammatory.

Biological mechanisms driving ageing.

The biological mechanisms driving the ageing process in many species have been proposed to consist of various responses to cell and organelle damage. They include the accumulation of senescent cells, altered nutrient sensing, reduced mitochondrial fitness and stem cell function. Inflammation is one of the key downstream mediators as senescent cells release pro-inflammatory cytokines.

Senescence-associated secretory phenotype (SASP).

Senescent cells are classically proliferatively quiescent but highly active metabolically. They have a rich secretory output termed the SASP, which contains pro-inflammatory cytokines and chemokines, matrix metalloproteinases and growth factors such as VEGF. The SASP is thought to be a key mediator of the ageing process.

Inflammageing.

Inflammageing describes the two to four fold increase in systemic levels of inflammatory cytokines (e.g. TNF, IL-1 β and IL-6) and reduced levels of anti-inflammatory cytokines (e.g. IL-10) seen with advanced age. The degree of inflammageing is associated with increased risk of a range of age-related diseases including cardiovascular disease, osteoporosis, cancer and dementia.

VO₂max.

VO₂ max is the maximum rate of oxygen consumption measured during incremental exercise. The value is a measure of an individual's cardiorespiratory fitness as it represents the maximum rate at which the heart, lungs and muscles can use oxygen during exercise.

Figure 1

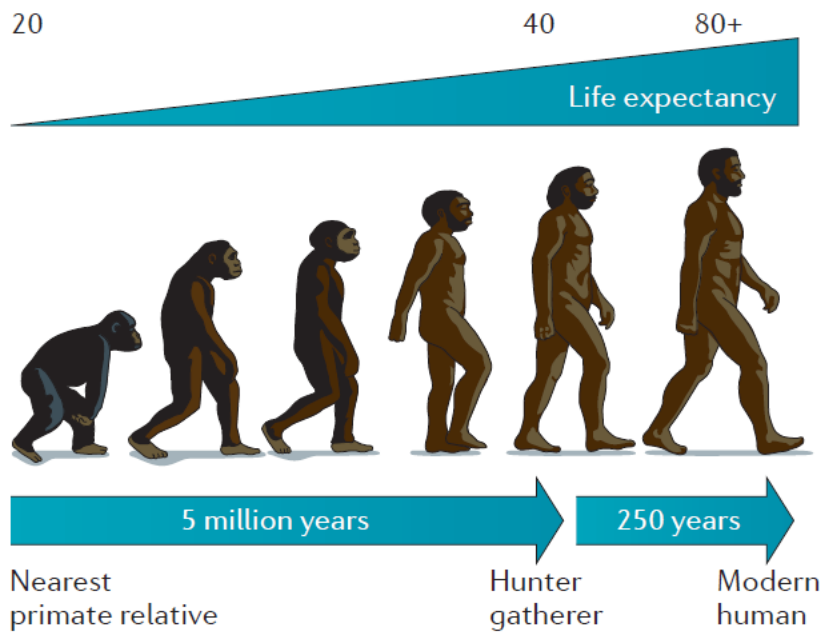


Figure 2

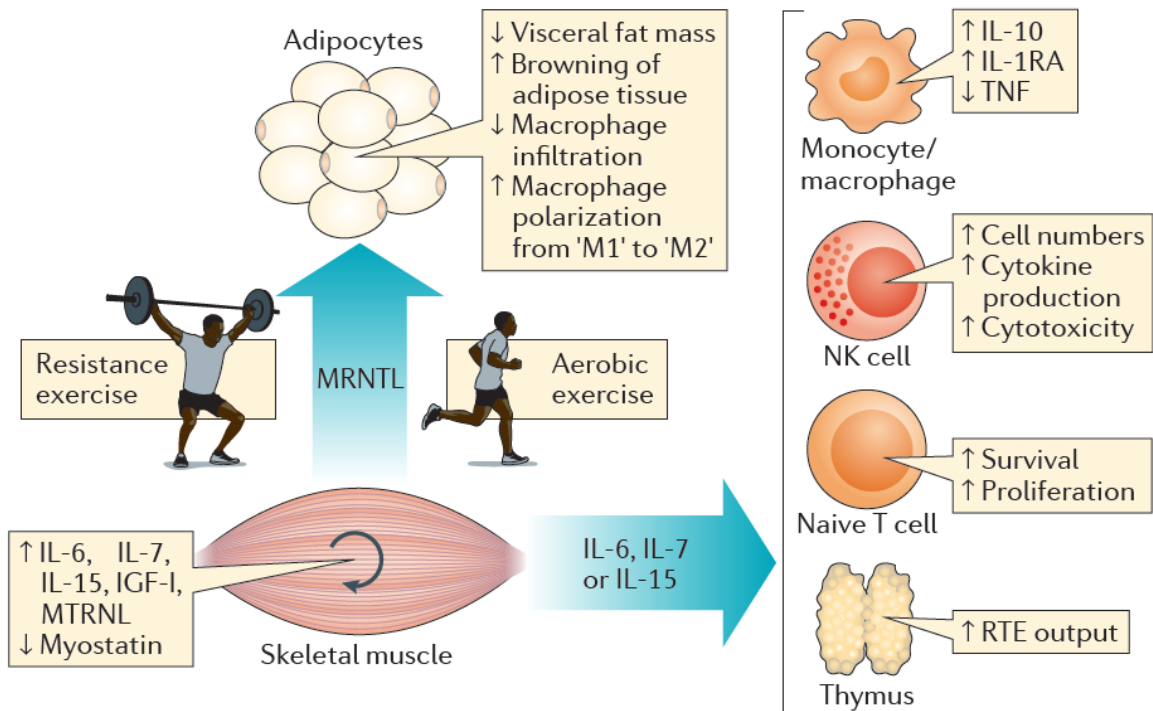


Figure 3

