Effects of vitamin D on health outcomes and sporting performance: Implications for elite and recreational athletes

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Abstract

The primary source of vitamin D is through synthesis in the skin, following exposure to sunlight containing ultraviolet B (UVB) radiation. Supply through skin exposure can be supplemented by the diet, but there are relatively few dietary sources, especially those which provide a large amount of vitamin D per serving. Research into the effects of vitamin D status in different population groups has become an increasingly popular topic. The current interest surrounding vitamin D research in sport remains focused on the potential ergogenic effects of vitamin D on physical performance. However, the relationship between vitamin D (dietary intake and status) and musculoskeletal health in university athlete cohorts residing at higher latitudes (>40°N) remains underinvestigated. Within this review, the possible physiological roles that vitamin D may play within sport performance for recreational and professional athletes, as well as military recruits, will be discussed. The focus will be on muscular strength, cardiovascular health and the incidence of illness, including upper respiratory tract infections. Specifically, the effect that vitamin D deficiency [defined as a plasma/serum 25-hydroxyvitamin D [25(OH)D] concentration of <25 nmol/l] may have on musculoskeletal health, including the incidence of stress fractures, is discussed. The review also seeks to highlight avenues for future research within vitamin D and sport, in particular for populations residing at higher latitudes (>40°N) where wintertime vitamin D deficiency is prevalent. It is hoped that this review will help to raise the awareness of the importance of existing advice in the UK for the avoidance of vitamin D deficiency and international vitamin D guidelines (such as in the US) on the achievement of vitamin D sufficiency [serum 25(OH)D >50 nmol/l] for optimum health and performance in athletes, both professional and recreational.

Keywords: immunity, musculoskeletal health, physical performance, university athletes, vitamin D

Introduction

Interest in vitamin D status within athletic populations has increased due to several recent reviews indicating that professional and elite level athletes are at risk of
vitamin D deficiency and insufficiency (Larson-Meyer & Willis 2010; Dahlquist, Dieter & Koehle 2015; Farrokhyar et al. 2015; Owens et al. 2018). However, the usefulness of vitamin D supplementation for sport performance is currently under debate within the sporting community, as there is conflicting evidence as to whether vitamin D supplementation actually improves physical performance. Whilst some reviews of cross-sectional or intervention studies make compelling arguments, there is currently no consistent evidence to suggest that vitamin D has a direct effect upon physical performance (Owens et al. 2018). This could be attributed to an over-reliance on cross-sectional studies used within many reviews, rather than randomised controlled trials investigating the direct influence of vitamin D supplementation or status on sport performance. Furthermore, the studies reviewed have also utilised a variety of supplementation protocols, methodologies, clinical categories for vitamin D status and methods for quantification of status (according to plasma/serum 25-hydroxyvitamin D concentration). This review aims to discuss the relevance of both established (e.g. for musculoskeletal health) and emerging (e.g. immune function and cardiovascular health) physiological roles of vitamin D, for those undertaking regular sport at different levels of participation. Whilst the focus is on the recreational athlete, findings from studies of elite and professional athletes are also included to enable the importance of vitamin D to both sporting performance and health outcomes to be put into the widest context possible with respect to physical activity levels.

**Overview of vitamin D physiology**

Vitamin D is not a ‘vital amine’ in the true sense of the word but rather it acts as a pro-hormone. There are two main forms of vitamin D: vitamin D$_2$ (ergocalciferol) and vitamin D$_3$ (cholecalciferol), which may be obtained from the diet or supplementation. However, the primary source of vitamin D$_3$ is endogenous synthesis in the epidermis of the skin upon exposure to sunlight containing ultraviolet B (UVB) radiation, which produces pre-vitamin D$_3$ from 7-dehydrocholesterol. Both forms of vitamin D are converted into the active metabolite, 1,25-dihydroxyvitamin D [1,25(OH)$_2$D], through two hydroxylation steps: firstly, in the liver where vitamin D is converted to 25-hydroxyvitamin D [25(OH)D], which is the major circulating vitamin D metabolite and the best clinical indicator of status, and a second hydroxylation step in the kidney, which converts 25(OH)D to 1,25(OH)$_2$D.

During the summer months in the UK and other areas of northern latitude, effective UVB radiation for vitamin D synthesis occurs from mid-morning (11:00) to mid-afternoon (15:00). However, from mid-October to the beginning of April, there is a lack of appropriate UVB radiation at more northerly latitudes (above 40°N of the equator) (Webb & Holick 1988). Furthermore, melanin, found in the epidermal layer of the skin, is the pigment primarily responsible for skin colour. It is efficient at absorbing UVB radiation at 290–700 nm, which includes the portion responsible for vitamin D$_3$ synthesis, thereby acting as a natural sunscreen (Wacker & Holick 2013). Therefore, a person with a darker skin tone requires at least 5–10 times longer exposure to UVB, compared to a person with a paler skin type (Holick 2017). As a result, ethnic groups with darker skin pigmentation, residing at higher latitudes, are at higher risk of deficiency and require a longer exposure time or higher dose of UVB, in contrast to those with paler skin (Clemens et al. 1982). In addition to this, culture has an important impact upon vitamin D synthesis, as religious clothing, or ‘covering up’, will reduce sun exposure. Therefore, individuals who tend to cover most or all of their skin when outside are at an increased risk of low vitamin D status. In addition to this, individuals who are vitamin D deficient during the winter months are at risk of an even lower vitamin D status in the spring (Todd et al. 2015).

Serum 25(OH)D is the circulating metabolite that is universally accepted as the principal measure of vitamin D status in humans, and the marker of vitamin D status utilised in all of the literature subsequently discussed throughout this review. However, there is a lack of agreement within the scientific community regarding what constitutes ‘deficient’ or ‘sufficient’ serum 25(OH)D status, as shown in Table 1. Furthermore, the UK does not have a clinical cut-off for a ‘sufficient’ 25(OH)D status within the general population, unlike the Institute of Medicine (IOM) (≥50 nmol/l) and the European Food Safety Authority (EFSA) (≥50 nmol/l). Table 1 also illustrates the current conflicting recommendations from different European and North American institutions regarding the dietary vitamin D intake required to meet these recommendations.

What is the vitamin D status of elite/professional athletic populations?

There is some evidence that professional athletes who reside at higher latitudes (≥40°N), or who train predominantly indoors for their respective sport, are at an elevated risk of 25(OH)D insufficiency.
(<50 nmol/l) or even deficiency (<25–30 nmol/l). A systematic review and meta-analysis of 23 studies investigating the prevalence of vitamin D insufficiency within professional athletes determined that 56% of the 2313 athletes examined were classed as ‘insufficient’ [defined by the authors as a 25(OH)D <80 nmol/l] (Farrokhyar et al. 2015). Notably, insufficiency rates were reported to be highest within the UK/Irish (70%; n = 495) and Middle Eastern (84%; n = 1283) athletic cohorts. These insufficiency rates could be attributed to the ethnic diversity within the Middle Eastern cohorts and latitude and low sunlight exposure during the summer months within the UK/Irish athlete cohorts. However, it is difficult to interpret the findings from this review as a particularly high clinical cut-off for ‘insufficiency’ was used, which the authors attributed to the heterogeneity in the cut-offs utilised within the 23 studies that were included; and to the inconsistency of current recommendations for vitamin D intake and status from different expert organisations (shown in Table 1). Moreover, there was also great heterogeneity between the methods used for the measurement of vitamin D status. Few studies measure vitamin D utilising what is arguably considered the ‘gold standard’, liquid chromatography-tandem mass spectrometry (LC-MS/MS) (Backx et al. 2016), which further confuses the evidence on the extent of vitamin D insufficiency or deficiency within professional athletes.

However, many professional athletes often attend training camps abroad in ‘sun holiday’ destinations at lower latitudes (where vitamin D$_3$ synthesis in the skin may be possible), and therefore they may not be considered as truly representative of recreational or university athlete populations. For example, a cohort of English professional Premier League footballers had a relatively high mean 25(OH)D status of 51 nmol/l in December, and a mean 25(OH)D status of 104 nmol/l in August (Morton et al. 2012), which is considerably higher than the average UK status for men and women (44.0 and 48.0 nmol/l, respectively), according to data from the National Diet and Nutrition Survey (NDNS) (Roberts et al. 2018). The higher vitamin D status of these professional footballers could have been due to match play, pre-season training camps or off-season sun holidays abroad during the summer months. Therefore, as studies of athletes may be subject to the influence of multiple confounders (such as season training camps and on-/off-season periods), a multi-site longitudinal study of elite athletes residing across different latitudes, of differing ethnicities and utilising the ‘gold standard’ practices of vitamin D status measurement is warranted, to better establish both the risk and the extent of vitamin D ‘deficiency’ within this population group. Indeed, such a study would be beneficial to educate athletes (and their coaches) on the importance of vitamin D, and of the potential detrimental effects of vitamin D deficiency, or potential benefits of a more ‘optimal’ status on sporting performance, is to be fully realised.

**What is the vitamin D status of university athletes?**

Although there is large body of evidence relating to elite level athletes and their vitamin D status, this is
not the case for university or recreational athletes, particularly with respect to their risk of 25(OH)D deficiency (<25–30 nmol/l). A recreational athlete is considered a physically active individual that participates in sport at an amateur, masters or club level, with the primary goal to be physically fit. Preliminary findings from studies conducted at lower latitudes have shown that 25(OH)D insufficiency (<50 nmol/l) or deficiency (<25 nmol/l or 30 nmol/l) is commonly observed within this particular population. A cross-sectional study conducted within the US (44.9°N) reported that 37.7% of the university athletes were found to be vitamin D insufficient [defined as 25(OH)D <80 nmol/l by the authors] during the spring (Fitzgerald et al. 2014). Similarly, another retrospective cross-sectional US (34.0°N; n = 223) study also found that 30.5% of their cohort presented with vitamin D insufficiency [according to the 25(OH)D cut-off used of <50–80 nmol/l] (Villacis et al. 2014). Another lower latitude cross-sectional study (30.5°N) found that 50% of a university athlete cohort (n = 40) presented with vitamin D insufficiency [defined as a 25(OH)D concentration <87 nmol/l] (Forney et al. 2014). However, all three of these US studies used very high cut-offs for vitamin D insufficiency [25(OH)D concentration <50–85 nmol/l], which makes it difficult to draw conclusions regarding vitamin D status in relation to physical performance outcomes. These studies suggest that there is a significant need to promote more awareness of vitamin D insufficiency across these younger and recreational sporting populations.

Studies conducted at different latitudes, including the US (Halliday et al. 2011; Fitzgerald et al. 2014; Villacis et al. 2014; Barcal et al. 2016; Jung et al. 2018), Europe (Koundourakis et al. 2014; Aydin et al. 2019) and the UK (Owens et al. 2014; Todd et al. 2017), also indicate that university and recreational populations are at risk of a low vitamin D status (<50 nmol/l). It is important to note that the cut-offs used within these university studies ranged from 25 to 80 nmol/l for 25(OH)D insufficiency and limited scientific justification was given for why they had chosen a particular cut-off for vitamin D status. Few discussed whether their cut-offs for vitamin D status were based upon a particular scientific body’s recommendations (such as the IOM), or their own, to improve the presentation of their data. Insufficient 25(OH)D concentrations have also been identified within different young athletic populations, where prevalence rates (defined by the authors as <80 nmol/l) were reported to be 74% of a group of wrestlers (Barcal et al. 2016), 37.7% of a group of ice hockey players (Fitzgerald et al. 2015), 13% of a group of swimmers and divers (Lewis, Redzic & Thomas 2013) and 30.6% of a group of jockeys (Wilson et al. 2012), which would suggest that there is a need to promote awareness of the importance of vitamin D for general health and physical performance (such as aerobic fitness and muscular strength) within young athletic population groups.

Latitude plays a vital role in the likelihood of whether an individual is susceptible to becoming vitamin D deficient [25(OH)D concentration <25 nmol/l] for part or most of the year. In a recent study, university taekwondo athletes residing at 37.6°N were found to have a low baseline 25(OH)D status of 28.8 nmol/l, which improved following supplementation of 125 μg/day over 4 weeks (Jung et al. 2018). Furthermore, judoka university athletes at 52°N also had a relatively low 25(OH)D status of 33 nmol/l during the winter (Wyon et al. 2016), which would be anticipated to fall further in the spring term due to a lack of UVB exposure during the winter months.

The vitamin D status of a physically active individual is also dependent upon the training environment for the sport, specifically during the summer time, as this is the optimal time of the year to synthesise vitamin D in the skin. Therefore, highly active individuals and university athletes who spend large amounts of time indoors competing or training are at risk of low vitamin D status. A retrospective study in the US (34.0°N) in 223 university athletes found that those classed as ‘indoor’ athletes were borderline significant to be more likely to be insufficient in vitamin D [defined as a 25(OH)D concentration <50 nmol/l] than the outdoor athletes [odds ratio (OR): 2.02 (95% CI: 0.99–4.11), P = 0.052] (Villacis et al. 2014). It is possible that this could be attributed to the smaller indoor athlete group (n = 38) recruited in comparison to the outdoor group (n = 185). This study also revealed that 64.9% of the darker skin tone athletes (Black and Hispanic athletes) were 25(OH)D ‘insufficient’ (<80 nmol/l) (Villacis et al. 2014). Following multivariate analysis only dark skin tone remained a significant predictor of vitamin D insufficiency [OR: 15.2, (95% CI: 7.5–30.5), P < 0.001]. A Japanese (35.8°N; n = 27) cross-sectional study on female university athletes also reported that indoor athletes had a lower vitamin D status when compared to outdoor athletes [25(OH)D concentration of 47.4 nmol/l vs. 79.9 nmol/l, respectively] during the spring (Maruyama-Nagao, Sakuraba & Suzuki 2016). These findings correspond with those reported by Farrokhyar and colleagues in their systematic review of professional athletes (Farrokhyar et al. 2015), which found that indoor athletes were at higher relative
risk of vitamin D ‘deficiency’ than their outdoor counterparts.

How aware are young athletes of the importance of vitamin D?

There is a need to promote more awareness of the potential for vitamin D deficiency (according to the Scientific Advisory Committee on Nutrition (SACN) cut-off for 25(OH)D concentration of <25 nmol/l) across the younger healthy populations within the UK, as vitamin D deficiency is related to poor musculoskeletal health. However, there is a lack of evidence of the prevalence of low vitamin D status in university or recreational athletes residing within Europe or the UK since the vast majority of research is based on US university athlete cohorts, which are not representative of European or UK populations due to the differences in latitude and food fortification programmes within the US (Calvo, Whiting & Barton 2004) as well as possible differences in the physical demands of university sport between the US and the UK. Sports participation or physical activity should be encouraged as part of a healthy lifestyle, thus helping to ensure the consolidation of bone mass during adulthood. Additionally, there is a lack of research on dietary intakes within this young adult cohort. A greater focus is also needed on university cohorts within the northern hemisphere, such as in the UK, where university sport is growing and is an integral part of many students’ experience, with 160 institutions in the UK hosting weekly BUCS (British Universities and Colleges Sport) competitions across 50 different disciplines, equating to approximately 6000 teams and over 100 championship events annually (BUCS 2017). Notably, SACN has also recognised that the vitamin D intake and status of this particular age group are limited and require more attention (SACN 2016).

A recent US (47.9°N) cross-sectional study in 81 university athletes evaluated the knowledge of vitamin D using an online questionnaire, comprised of five vitamin D-related questions, such as ‘how much have you heard about vitamin D?’ (Leitch et al. 2019). Answers utilising the Likert scale ranged from ‘never’ to ‘a lot’. Responses to the questionnaire revealed that, although they identified vitamin D as beneficial to sporting performance/overall health, university athletes did not express a concern regarding their vitamin D status. They also reported that they considered themselves ‘unlikely’ to ‘very unlikely’ to be deficient in vitamin D, which highlights that although athletes are aware of the importance of vitamin D, they are unaware that they may be at risk of deficiency.

What physiological roles does vitamin D play in sport?

Vitamin D and bone health

Vitamin D has a well-established function in bone health, due to its role in calcium absorption and utilisation for mineralisation of the skeleton. In the absence of the active form of vitamin D [1,25(OH)2D], calcium absorption can be limited, as only 10–15% of dietary calcium is absorbed (Holick 2017). However, when plasma 25(OH)D levels are in excess of, or equal to 75 nmol/l, it estimated that ≥30% of calcium can be absorbed from the diet, thereby providing a greater amount of calcium, which may help improve bone density (Larson-Meyer 2015). Avoidance of vitamin D deficiency [25(OH)D concentration >25 nmol/l] is considered an important factor in maximising the amount of bone mass attained during childhood and puberty – the optimal period for doing so in order to reduce risk of developing osteoporosis (a disease characterised by porous and weak bone) later in life (Cosman et al. 2014).

It is well-established that physical activity can improve bone strength (Kohrt et al. 2004). Bone is not inert, rather it is continuously remodelled through the recruitment of osteoblasts (responsible for forming bone) and osteoclasts (responsible for bone resorption). Bone structure can be altered by forces placed upon it; Wolff’s law (Turner 1992) predicts that increasing the load through physical activity improves bone strength in a site-specific manner. Previous studies have shown that exercise-related improvements in bone strength are dependent on the type of physical activity (Weidauer et al. 2014). The three types that are particularly effective in enhancing bone strength are as follows: (1) strength training that incorporates large load volumes; (2) high-impact training; (3) plyometrics (jumping exercises) (Martyn-St James & Carroll 2010; Gregov & Sala 2014). Two studies that explored the interrelationship between vitamin D status and bone density in athletes reported that there was no association between 25(OH)D deficiency (defined as <30 nmol/l) and bone mineral density (BMD; a marker of bone health) in either recreational or professional athletes (Halliday et al. 2011; Allison et al. 2015a), respectively. However, these studies did not investigate the association between vitamin D status and the geometrical changes in bone structure. Therefore, even though no association between vitamin D status and BMD was reported in these two studies, it is possible there could have been changes to the bone composition that affected overall bone strength and,
therefore, the risk of stress fractures, as discussed in the next section.

Vitamin D and stress fractures

Emerging evidence suggests that vitamin D may be important for stress fracture prevention in athletic populations (Lappe et al. 2008; Davey et al. 2016; Griesshober et al. 2018). Stress fractures commonly occur in the tibia, fibula and femur bones of the leg, as well as the tarsal and metatarsal bones of the foot. These can be attributed to a sudden increase in physical activity, decreased lower extremity strength, low bone density and/or history of menstrual disturbance (Moran et al. 2013). Stress fractures have been reported most commonly within prospective studies of military recruits and have been attributed to the increased physical activity during intensive training programmes. For example, Davey et al. (2016) reported that stress fractures occurred in 7% of royal marines (n = 1082) during recruitment training (an arduous training programme that lasts 32 weeks). It was found that a low vitamin D status [plasma 25(OH)D <50 nmol/l] was prospectively associated with a significantly increased risk of stress fractures. Additionally, another UK study with 37 injured British Army recruits found that recruits who had a sufficient 25(OH)D level (>50 nmol/l) at the time of injury recovered more quickly from stress fracture injury (Richards & Wright 2018). This relationship between low vitamin D status and increased stress fracture incidence is consistent with other prospective military-based investigations conducted in Finland (Ruohola et al. 2006) and the US (Lappe et al. 2008). Lappe and colleagues conducted a double-blind, randomised controlled trial with 3700 female US navy personnel to investigate the effect of vitamin D and calcium supplementation (2000 mg/day of calcium; 800 IU/day of vitamin D) and the incidence of stress fractures. In agreement with Davey and colleagues’ findings, supplementation significantly reduced the risk of stress fracture (by up to 20% vs. the control group) despite the negative influences certain lifestyle factors may exert upon bone health (such as limited dairy food consumption, alcohol use, ethnicity and genetics).

Stress fractures in elite athletes directly affect training and competition. However, there is a lack of evidence on the relationship between stress fractures and vitamin D status in either professional or recreational athletes, including whether supplementation can reduce the risk of fractures. Studies in this area are complex, as many variables other than vitamin D status can contribute to a stress fracture, including overtraining, poor quality diet, smoking, age and amenorrhoea (absence of menstruation) in female participants (Mayer et al. 2014). In a study of 25 female distance runners followed for 2 years, higher daily consumption of calcium, skimmed milk, milk and servings of dairy products was found to be associated with a 68% lower incidence of stress fractures (Nieves et al. 2010). Also, vitamin D intake predicted an increase in spine and hip BMD among this cohort, assessed using a dual-energy X-ray absorptiometry scan. In another observational study conducted in female adolescent athletes participating in different sports by Sonneville et al. (2012), it was found that, after adjusting for confounders (such as age and body mass), those in the highest quintile of vitamin D intake had a 50% lower risk of stress fractures when compared to those who were in the lowest quintile of intake, but there was no evidence of a protective association between dairy intake and stress fracture risk. However, in a study of university athletes, no association was found between the frequency of injury and vitamin D status (Halliday et al. 2011). Further research is needed to explore the effects of combined vitamin D and calcium intake, or vitamin D status, on risk of injury and stress fracture prevention in athletic populations.

Vitamin D and muscle health

There is evidence to suggest that vitamin D plays a significant role in muscular function (Gunton & Girgis 2018). However, research into the potential benefit of vitamin D on muscular strength or power has been inconclusive. This is because there is an ongoing debate as to whether the vitamin D receptor (VDR) is, in fact, present within muscle. Wang and DeLuca (2011) provided evidence that the VDR remains undetectable in mature skeletal muscle, following staining with an antibody that does not react with the proteins in tissues other than the VDR, and which were prepared using tissue from the VDR knockout mouse. This was a notable limitation of a previous study on the detection of VDRs within human skeletal muscle tissue (Bischoff et al. 2001), thereby producing false-positive results. The authors concluded that the VDR was undetectable in skeletal, cardiac and smooth muscle and that perhaps the role of vitamin D on muscle does not involve the VDR. However, this is of much dispute, as other experts in the field have proposed the mechanistic effect of vitamin D within the muscle to be that it increases the sensitisation of calcium-binding
sites at the sarcoplasmic reticulum (a membrane-bound structure found in muscle cells, with the principal function of storing calcium ions; \( \text{Ca}^{2+} \)), thereby leading to the exposure of active binding sites within the muscle, which prompts muscular contraction (Girgis et al. 2013). However, inadequacies in the technical processes (such as immunocytochemical staining) to detect VDRs may be responsible for the lack of results on the isolation of VDRs in human muscle cells (Ogan & Pritchett 2013).

Research has demonstrated improvements in muscular function using isokinetic dynamometry (a means of measuring muscular force) following supplementation with vitamin D (Owens et al. 2014), although this was only demonstrated in previously deficient participants (\( \leq 30 \text{ nmol/l} \)). Subsequent to this, a systematic review and meta-analysis examining the effects of vitamin D supplementation on upper/lower body muscular strength identified seven studies where baseline serum 25(OH)D levels were lower than that deemed ‘sufficient’ by the IOM (<50 nmol/l), although they were not exclusive to athletic populations (Tomlinson et al. 2015). Outcome measures varied between the included studies, including isokinetic dynamometry, leg/chest bench press and isometric quadriceps contractions. The meta-analysis revealed that vitamin D supplementation improved lower body muscular strength [standardised mean difference: 0.32, (95% CI: 0.01–0.63) \( P = 0.04 \)], defined as the maximum force-generating capacity of a muscle or a group of muscles. However, this meta-analysis did not evaluate the direct effects of vitamin D supplementation on upper/lower body muscular power (the rate of work performed by a muscle or a group of muscles). Therefore, strength and power may have different responses to vitamin D supplementation, which could be attributed to the different muscle fibres recruited for muscle strength (which uses fast- and slow-twitch muscle fibres) or power (fast-twitch muscle fibres), and this warrants further investigation in future studies. Further research is also needed to explore the role of vitamin D in muscular function in healthy adult athletic populations, and the potential detrimental effects of vitamin D deficiency/insufficiency on muscle power output.

There have only been a few studies that have explored the effect of vitamin D supplementation on muscular power rather than strength. Close et al. (2013a) reported a significant improvement following 8 weeks of vitamin D3 supplementation (5000 IU/day or 125 \( \mu \text{g/day} \)) on 14 professional footballers’ 10 m sprint times and vertical jump height. Both of these activities recruit type II muscle fibres (or ‘fast-twitch’ muscle cells), which are mobilised to produce the explosive power that is required to jump and sprint. However, the supplemented group had lower 25(OH)D status at baseline vs. the placebo group, which could account for this improvement in muscular power and the authors failed to provide sufficient baseline and post-intervention tabulated data on the vitamin D status of their participants, a criticism which is also highlighted in Tomlinson and colleagues’ review (2015). In contrast, markers of muscular strength within the same study showed no improvement but were only measured in 10 participants, which reduces the power of the study to detect a difference. Other studies have also found no improvement in muscular power, including another UK study of 30 club-level athletes conducted by the same group, which found predictors of muscular power were not improved following supplementation of 20 000 to 40 000 IU/week (500 to 1000 \( \mu \text{g/day} \)) of vitamin D over a 12-week period (Close et al. 2013b). It may be that the potential ergogenic effects (a nutritional ergogenic aid can directly improve physiological variables associated with exercise performance, providing a competitive edge) of vitamin D supplementation are only exhibited in recreational/professional athletes with 25(OH)D deficiency or insufficiency (Close et al. 2013b; Forney et al. 2014; von Hurst & Beck 2014; Fitzgerald et al. 2015). Further investigation is warranted into the relationship between vitamin D status and muscular strength in a larger group of athletic individuals, with consideration given to baseline vitamin D status. Furthermore, a dose-response study would provide greater insight as to whether enhanced vitamin D status is associated with greater muscle power and strength.

**Vitamin D and immune function**

Interest in exercise immunology (the study of the interaction between physical, environmental and psychological factors on immune function) has significantly increased over the past 30 years. This is due to investigations examining the prevalence of upper respiratory tract infections (URTIs) in athletic populations and the associations between sport/exercise and immunology (Nieman & Wentz 2019). It has been reported that immune function can be compromised by over-training, psychological stressors, disrupted sleep patterns and poor nutrition (Walsh et al. 2011). Therefore, to cope with high training volume and frequency load, it is important for professional
athletes to obtain optimal sleep and nutrition to help maintain a healthy immune system (Maughan et al. 2018). Amongst the many possible roles vitamin D has in the human body, there is evidence for an association between low vitamin D status and illness. For example, 9377 individuals in the 1958 British Birth Cohort study (>45 years) with a higher vitamin D status, likely achieved during the summer months, had a lower incidence of respiratory infections following health questionnaire data collated at a single time point (Berry et al. 2011). In addition to this, a systematic review and meta-analysis of randomised controlled trials found that daily or weekly vitamin D supplementation resulted in a statistically significant reduction in the proportion of participants experiencing at least one acute respiratory tract infection (Martineau et al. 2016). Notably, this review also observed that the protective effects of vitamin D supplementation were strongest within those with 25(OH)D deficiency (<25 nmol/l) at baseline.

Vitamin D receptors and the enzyme 1-α hydroxylase (which hydroxylates 25(OH)D to the active form 1,25(OH)D) (He et al. 2016) are present in many cells of the immune system, suggesting that it is functionally important. Examples of cells containing VDR and 1-α hydroxylase are T and B lymphocytes and neutrophils. Vitamin D can also up-regulate antimicrobial peptides (Owens et al. 2018). These immune cells can down-regulate pro-inflammatory cytokines (proteins that are secreted by other cells of the immune system), such as tumour necrosis factor-alpha (TNF-alpha) and interleukin-6 (IL-6). However, the mechanisms behind the reduced inflammation associated with vitamin D remain poorly understood. It is suggested from studies investigating rheumatoid arthritis that vitamin D may play a role in T-cell proliferation, thereby inhibiting the expression of inflammatory cytokines such as IL-6, IL-17 and IL-23 (Gopal et al. 2019). Moreover, vitamin D can also up-regulate the production of anti-inflammatory cytokines (such as IL-4, IL-10 and IL-13) (Larson-Meyer 2015; Owens et al. 2018).

Innate (otherwise known as ‘inherited’) immunity is negatively affected by low circulating vitamin D levels because the production of cathelicidin (an antimicrobial protein critical for innate immunity) is dependent upon vitamin D (Hewison 2012). Vitamin D2 also contributes to the defence against pathogens such as Mycobacterium tuberculosis (Liu et al. 2007) through cathelicidin (Yuk et al. 2009; Jo 2010). Toll-like receptors are activated, causing the up-regulation of VDRs, which therefore induce the transcription of vitamin D-responsive genes leading to the production of cathelicidin. Vitamin D has an immunomodulatory (it can modify the function of the immune system) effect on T and B lymphocytes in acquired immunity (Owens et al. 2018).

The effect of vitamin D supplementation on university athletes’ immune responses was investigated in a UK study (He et al. 2015). Thirty-nine participants were provided with a vitamin D3 supplement (15 μg/day) or placebo for 14 weeks, and effects on the salivary secretion of immunoglobulin A (SIgA) and cathelicidin were examined. Salivary SIgA and plasma cathelicidin concentrations significantly increased over time (He et al. 2015). In another 16-week (n = 181) prospective study, the same group found university athletes with a higher 25(OH)D status (>90 nmol/l, n = 26) had significantly higher cathelicidin levels than those classed as vitamin D ‘deficient’ [25(OH)D concentration <30 nmol/l; n = 27]. In addition, athletes in the ‘deficient’ group reported (in a validated health questionnaire) a higher incidence of URTI, of a longer duration and with a higher perceived severity score than athletes with a higher 25(OH)D status (He et al. 2013), suggesting that vitamin D ‘insufficiency’ or ‘deficiency’ may increase the risk of URTI. The findings by He et al. (2013) are consistent with other earlier studies showing that low 25(OH)D status is associated with an increased frequency of URTI in professional athletes (Laakski et al. 2006; Willis et al. 2012) and university athletes from the US (Halliday et al. 2011). However, further research is warranted on the relationship between URTI incidence and vitamin D status in athletic and military populations, to establish whether vitamin D supplementation may be useful for URTI prevention in those who are vitamin D sufficient.

Vitamin D and cardiovascular health

Research in relation to cardiovascular function and vitamin D was first conducted in Sprague-Dawley rats, where it was found that the vitamin D-deficient rats exhibited higher contractile responses of isolated cardiac and vascular smooth muscle, and hypertension (Simpson 1983).

As a result of training, elite athletes would be expected to present with a different cardiac morphology (often referred to as the ‘athlete’s heart’) when compared to their inactive counterparts (Weiner & Baggish 2012). For example, athletes and well-trained individuals that participate in dynamic
exercises such as long-distance running have an increased cardiac output, driven by an elevated stroke volume and lower heart rate (McArdle & Katch 2010). Indeed, it is well-established that the physiology of the heart is dependent upon the modality of sport, age, ethnicity, genetics and body composition (Allison et al. 2015b). Although research to date has not focused on the direct effects of vitamin D supplementation on healthy cardiac morphology, a cross-sectional study conducted in 506 international professional athletes (football, handball, volleyball and basketball players) from Qatar found that those with a 25(OH)D concentration classed as ‘severely-deficient’ or ‘deficient’ (<25 and 25–50 nmol/l, respectively) had a smaller aortic root, right atria, left atria diameters, intraventricular septum diameter, left ventricular diameter and left ventricular mass (Allison et al. 2015b), which are likely to negatively affect cardiac output. However, it is not possible to infer a direct relationship between vitamin D status and cardiac morphology, due to the lack of evidence within the current literature required to establish causality and potential mechanisms underpinning these associations. The relationships between vitamin D status and cardiac outcomes remained significant when controlling for body composition, age and ethnicity for left atrium, intraventricular septum during diastole, left ventricular diameter during diastole, left ventricular mass and left ventricular volume during diastole (Allison et al. 2015b). However, the researchers did not control for the training modality, and it was not specified which sporting group presented with a lower vitamin D status. Cardiorespiratory fitness in competitive ice hockey athletes was not associated with vitamin D status following a skate treadmill graded exercise test following correlation coefficient analysis ($r = -0.103$, $P = 0.469$) (Fitzgerald et al. 2014). Forney et al. (2014) also found no correlation between the cardiorespiratory fitness and vitamin D status in a group of female athletes ($r = -0.214$, $P = 0.379$). However, the 25(OH)D ‘sufficient’ (>87 nmol/l) male university athletes had a 20% higher VO2max when contrasted to their ‘insufficient’ (<87 nmol/l) male peers. This could be because male participants had a slightly lower vitamin D status than female athletes (mean values: 33.0 vs. 36.7 nmol/l, respectively) and had a greater range of 25(OH)D concentrations (46–124 vs. 48–173 nmol/l, respectively). Thus, the extent of how vitamin D status may directly influence cardiovascular health remains undetermined, highlighting that further evidence from prospective studies is required.

**Advice for healthcare professionals working with athletes**

The routine screening of vitamin D status (when available) may be beneficial to healthcare professionals working directly with athletes. When the routine screening of vitamin D status is not available, special attention should be paid to those that present with an increased frequency of illness, and those with bone and/or joint injuries and muscular pain, since these are common symptoms of long-term vitamin D deficiency or BMD (Cashman 2019). Furthermore, those who are at risk of eating disorders (such as continuous restricted energy intake, often associated with poor BMD; anorexia nervosa), reside at a high latitude (>40°N) and predominantly train indoors (such as gymnasts, swimmers and basketballers) should also be monitored for 25(OH)D deficiency (<25 nmol/l).

Total vitamin D intake among UK adults is typically below the reference nutrient intake (RNI) for vitamin D of 10 µg/day, with men and women (aged 19–64 years) consuming 4.5 and 3.9 µg/day on average.

**Table 2** Dietary sources of vitamin D (PHE 2019)

| Food and shellfish       | Vitamin D content (µg per 100 g/100 ml) |
|--------------------------|-----------------------------------------|
| Grilled herring          | 16.1                                    |
| Canned pink salmon in brine | 13.6                                  |
| Grilled salmon           | 7.8                                     |
| Grilled kipper fillet    | 9.0                                     |
| Baked rainbow trout fillet | 8.2                                   |
| Smoked mackerel          | 8.2                                     |
| Tinned sardines in tomato sauce | 3.3                                   |

| Milk and milk products   | Vitamin D content (µg per 100 g/100 ml) |
|--------------------------|-----------------------------------------|
| Build-up powdered sachet (shake) | 1.7                                     |
| Fortified soya milk      | 0.8                                     |
| Skimmed milk, dried      | 0.8                                     |
| Custard, confectioners’  | 0.8                                     |
| Horlicks, powder         | 18.5                                    |

| Animal products          | Vitamin D content (µg per 100 g/100 ml) |
|--------------------------|-----------------------------------------|
| Lamb leg, roast          | 0.7                                     |
| Beef, roast              | 0.8                                     |
| Comed beef, canned       | 1.3                                     |
| Grilled bacon rashers    | 0.8                                     |
| Grilled pork sausages    | 1.1                                     |
| Fried lamb’s liver       | 0.9                                     |
| Chicken’s egg, raw       | 3.2                                     |

| Non-animal based products| Vitamin D content (µg per 100 g/100 ml) |
|--------------------------|-----------------------------------------|
| Fortified, low-fat spread, polyunsaturated | 8.4                                     |
| Baking fat/margarine     | 8.8                                     |
| Bran type cereal, fortified | 3.9                                   |
| Breakfast cereal, cornflakes, fortified | 4.7                                     |
respectively, according to data from the NDNS (Roberts et al. 2018). This includes intakes of vitamin D from both the diet and supplements. The relatively few foods that provide a source of vitamin D in the diet include oil-rich fish, egg yolk, liver, red meat and fortified foods (e.g. breakfast cereals and fat spreads). Oil-rich fish provides the richest natural source of vitamin D, and the current UK dietary advice is to eat at least two portions (140 g) of fish per week, one of which should be an oil-rich fish portion. However, NDNS data indicate that less than a quarter of the UK population consume oil-rich fish, and even among these individuals, vitamin D intakes may fall short of recommendations (Roberts et al. 2018).

As only a limited number of foods naturally contain vitamin D (see Table 2), it may be beneficial to provide information to athletes regarding these foods that are a source of vitamin D, to help them to meet UK dietary recommendations (10 µg/day; PHE 2016). Special attention should also be paid to athletes that are vegan, as most dietary sources of vitamin D are derived from animal products, as shown in Table 2. A recent cross-sectional study from Denmark (55.7°N) revealed that only 46% of 78 healthy vegan adults were 25(OH)D sufficient (>50 nmol/l), in contrast to the omnivore group (86%) (n = 82; Hansen et al. 2018). The vegan group were also more likely be 25(OH)D deficient (<25 nmol/l) after adjusting for season, age, sex and adiposity [OR = 26 (95% CI: 2, 280), P = 0.007]. Furthermore, Hansen et al. also observed that the dietary intake of vitamin D from food was minimal when contrasted to omnivores (0.0 vs. 3.0 µg/day; P < 0.001). However, to the authors’ knowledge,

Vitamin D: Practical Advice for UK Sporting Individuals

**Summer**

High UVB: 11-3pm ONLY

Obtain safe sunlight exposure (between 15-20 minutes only) and apply sunscreen immediately after this within the time frame stated above.

Indoor athletes (e.g basketballers, netballers, gymnasts etc.) are particularly encouraged to seek safe sunlight exposure during this time frame.

During this time frame ensure that either face, arms or legs are uncovered for the 15-20 mins of safe sunlight exposure. This will ensure that vitamin D can be synthesised in the skin.

**Winter**

Vitamin D supplementation should be considered in the wintertime as it is difficult to obtain 10µg/d from foods

Foods that are a source of vitamin D*:

1. Fortified cereals: 4.7µg
2. Eggs: 3.9 µg
3. Grilled Salmon fillet: 7.8 µg
4. Tinned sardines: 3.3µg
5. Pork Sausages: 1.1µg
6. Fortified soya milk: 0.8µg

**SAFETY**

Avoid getting sunburn

Toxicity is rare but supplementation protocols must be monitored to prevent this from occurring

If you are concerned whether you are at risk of deficiency in vitamin D, discuss this with your GP or Team Medie to check and/or monitor your vitamin D levels

Current UK recommendations**: 10µg/d

References:

*Public Health England. (2019). McCance and Widdowson’s Composition of foods integrated dataset
**Scientific Advisory Committee on Nutrition and Department of Health. (2006) Vitamin D and Health.

Figure 1 Practical advice for UK sporting individuals. Note: This is a newly devised infographic, which the authors have designed on the collective information that they consider to be available for vitamin D and health advice for sporting individuals specifically as there are currently no recommendations available for athletic populations. [Colour figure can be viewed at wileyonlinelibrary.com]
there are no studies available regarding the 25(OH)D status of vegan athletes. Current UK advice is to consider supplementation of vitamin D (10 µg/day) during the winter/spring (PHE 2016). Vitamin D₃ supplements made utilising lanolin (an extract from sheep’s wool) will need to be avoided by vegans; however, vitamin D₃ supplements made from lichens are suitable (Spiro & Buttriss 2014). Safe sunlight exposure should also be encouraged during the summer months within the UK (between early May and September) from 11:00 to 15:00. During the summer months (between 11:00 and 15:00), athletes should ensure that parts of their body are uncovered for 15–20 minutes of sunlight exposure, which can include face, arms and legs. Sunscreen should be applied immediately after this and the skin should not be allowed to burn (Fig. 1).

**Vitamin D supplementation within professional athletes**

There are currently no guidelines in place for vitamin D supplementation in either professional or recreational athletes. However, the International Olympic Committee (IOC) and researchers within the area of vitamin D and sport (Larson-Meyer 2015; Todd et al. 2015; Farrokhyar et al. 2017; Owens et al. 2018) are in agreement that the regular monitoring of vitamin D status is imperative for the health and wellbeing of athletes. In addition, the IOC suggests that vitamin D should be supplemented (according to the US general population guidelines; 15–20 µg/day) dependent upon the athlete’s skin type and level of UVB exposure (Maughan et al. 2018), although there is no supplementation protocol provided for athletes. Despite the lack of vitamin D status reference ranges and intake guidelines for professional/recreational athletes, different athletes and sport teams implement their own supplementation guidelines, or follow the dietary recommendations for the general population, according to current government recommendations (such as 10 µg/day for the UK) (PHE 2016). However, it is also important to state that currently there are no ergogenic effects associated with an increased intake of vitamin D when the athlete is already 25(OH)D sufficient (>50 or >75 nmol/l). Therefore, healthcare professionals should focus upon the correction of 25(OH)D deficiency (<25 nmol/l), as this is closely associated with stress fractures, increased illness frequency, reduced BMD and even reduced muscular strength (Owens et al. 2018).

**Conclusion**

It is essential for athletes, both elite and recreational, to avoid vitamin D deficiency [a 25(OH)D concentration <25 nmol/l] year-round. This is particularly important when residing at latitude where UVB exposure is negligible during the winter months. Monitoring vitamin D status of athletic populations could be a useful way to identify individuals who may be at increased risk of stress fractures during intensive training and provide an opportunity to disseminate advice for improving vitamin D status. Maintaining an adequate vitamin D status may also confer additional health benefits for athletes in relation to musculoskeletal health (Lappe et al. 2008; Davey et al. 2016) and immunity (He et al. 2015).

Overall, as illustrated by the studies described throughout this review, there is an inconsistency regarding what constitutes an ‘optimal’ vitamin D status in healthy young adults. Numerous studies state different 25(OH)D cut-off values from different government recommendations [as highlighted within the systematic review by Farrokhyar et al. (2015)]. Thus, the interpretation of results for informing current knowledge on vitamin D and sport is indeed difficult, as multiple definitions for a ‘deficient’ or ‘insufficient’ vitamin D status are discussed. Moreover, multiple studies investigating vitamin D and sporting performance within university or recreational athletes are cross-sectional; thus, their results are limited in terms of ability to demonstrate the direction of the association. Consequently, some systematic reviews have excluded studies due to heterogeneity in the musculoskeletal outcome measures employed (from handgrip strength to isokinetic dynamometry) and particularly for serum/plasma 25(OH)D concentrations that constitute vitamin D ‘deficiency’ (25–30 nmol/l) (Farrokhyar et al. 2015). Thus, future trials on athletes should consider the measurement of vitamin D status within athletic groups residing outside the US, including their baseline status, ethnicity, the type of sport they participate in (indoor/outdoor), utilisation of consistent methodologies to measure serum/plasma 25(OH)D status (such as LC-MS/MS), as well as relevant performance outcomes and, finally, recruit an ethnically diverse group.

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Conflicts of Interest

The authors have no conflicts of interest to declare.

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