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Sedentary behaviour, physical activity and cardiometabolic health in highly trained athletes: A systematic review and meta-analysis

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Abstract

Prolonged periods of sedentary time appear to increase the risk for the development of several chronic conditions and all-cause mortality, even when moderate-to-vigorous physical activity (MVPA) is taken into consideration. However, whether the beneficial health effects of MVPA in highly active individuals remain present when leisure time is spent sedentary remains speculative. Therefore, we systematically evaluated off-training sedentary behaviour and physical activity levels in athletes. Studies were collected from four bibliographic databases (PubMed, Embase, Web of Science and The Cochrane Central Register of Controlled Trials). Studies were eligible for inclusion if they evaluated sedentary behaviour and physical activity levels among athletes. Data from athletes were compared with the general population and pooled using a random-effects model. After deduplication 3104 were identified of which 13 studies met inclusion criteria. Compared to the general population, athletes spent significantly more time in sedentary behaviour (+79 min/day; 95% confidence interval [CI]: [41, 65] min/day; p<0.001). In addition, athlete individuals spent less time in light intensity physical activity (-92 min/day; 95% CI: [-117, -66] min/day; p<0.001) and had increased levels of moderate-to-vigorous intensity physical activity (+62 min/day; 95% CI: [38, 85] min/day; p<0.001) compared to the general population. Athletes exceed the average time spend sedentary per day and make them even more sedentary compared to the general population.

Introduction

Physical inactivity is one of the major contributing factors to the development of chronic diseases and highly correlated with increased all-cause mortality (Lee et al., 2012). Recent data indicate that global physical inactivity is responsible for more than five million deaths annually and thereby categorized as the fourth leading cause of global mortality (Booth, Roberts, & Laye, 2012; Lee et al., 2012).

During the last decade an exponential growing number of scientific studies investigated detrimental effects of sedentary behaviour on health (Biddle et al., 2016; Wilmot et al., 2012). Here, sedentary behaviour is defined as "any waking behaviour, characterized by a low energy expenditure (≤1.5 METs), while being in a sitting or reclining posture" (Tremblay et al., 2017). Interestingly, prolonged periods of sedentary time appear to increase the risk for the development of several chronic conditions and all-cause mortality, independent of moderate-to-vigorous physical activity (MVPA) (Biddle et al., 2016). In fact, increasing evidence now suggests that the recommended daily MVPA based on the current guidelines from the World Health Organization possibly do not compensate the negative health impact which arise from prolonged periods of sitting (Duvivier et al., 2018; Henson et al., 2013; van der Velde et al., 2018). In this respect, it has become evident that frequent, even low-intensity, interruptions during extended periods of sitting are required for good cardiometabolic health (Duvivier et al., 2013). Although the total amount of daily MVPA appears relatively stable, people tend to compensate their exercise training related energy expenditure by decreasing their physical activity (PA) levels and increasing the time spend in sedentary behaviours throughout the rest of the day (Duvivier et al., 2018; Henson et al., 2013; van der Velde et al., 2018). In keeping with this line of reasoning, both PA and sedentary time seem to interact and should be integrated to a more holistic 24-hour approach involving different levels of PA and sedentary behaviour (Sperlich & Holmberg, 2017). A recent harmonized meta-syntheses indicated that the association between self-reported sitting, cardiovascular disease and all-cause mortality are only partially independent of PA, but were particularly evident in those who undertake insufficient PA (<150min/week) (Ekelund et al., 2016). Here, it appears that individuals engaging in high levels of PA might eliminate the increased risk of all-cause mortality associated with sedentary behaviour. Highly active individuals competing in physically demanding sports easily meet the recommended guidelines on PA to accrue cardiometabolic health benefits. However, whether the beneficial health effects of MVPA in these highly active individuals are attenuated when leisure time is spent sedentary remains speculative. In this respect, it has already been shown that athletes could have serious health complications including the metabolic syndrome (Buell et al., 2008; Guo, Zhang, Wang, Guo, & Xie, 2013; Tucker et al., 2009), which may be (at least in part) due to increased amounts of time spend in off-training sedentary behaviours. Although it is generally known that sedentary behaviour has independently been associated with higher levels of adiposity and impaired cardiometabolic health, it is unclear whether this independent relationship still exists in highly trained athletes. Indeed, a previous study found that non-exercise activity thermogenesis did not differ between sedentary individuals and athletes, suggesting comparable sedentary behaviours between these people (Alméras, Mimeault, Serresse, Boulay, & Tremblay, 1991). This suggests that the time spent sedentary may be more equal between athletes and non-athletes as previously thought. Therefore, this study aims to systematically evaluate off-training sedentary behaviour and PA levels in athletes. In addition, an overview will be provided with regard to the association between sedentary behaviour and cardiometabolic health. A greater understanding of these behaviours could contribute to a better insight to the sedentary behaviour paradigm.

2 METHODS

This systematic review was registered in the PROSPERO international prospective register of systematic reviews (registration number: CRD42020210508) and was performed in accordance with The Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) statement (Liberati et al., 2009; Moher, Liberati, Tetzlaff, Altman, & Group, 2009).

2.1 Data sources and search strategies

Studies were collected (from inception until May 2020) using computer-based searches in the PubMed, Embase, Web of Science and The Cochrane Central Register of Controlled Trials (CENTRAL) electronic databases. Database specific search strategies were developed with the guidance of a professional clinical librarian. The database searches were performed using three main concepts: athletes, PA and sedentary behaviour. For each main concept relevant related terms and keywords were included in the sensitive search (details presented in Appendix S1). The systematic search was limited to the English, German and Dutch language.

2.2 Eligibility criteria

Inclusion criteria to select studies were: 1) Study population: competitive and recreational athletes aged 18 years or older. Competitive athletes are described as individuals of young or adult age, either amateur or professional, who engaged in regular exercise training and participates in official sports competition (McKinney, Velghe, Fee, Isserow, & Drezner, 2019). As a distinction, recreational athletes engage in sports for pleasure and leisure-time activity, whereas competitive athletes are highly trained with a greater emphasis on performance and winning. In a proposed classification of athletes based on the minimum volume of exercise, 'elite' athletes generally exercise ≥10 h/week, 'competitive' athletes (high school, college, and older [master] club level athletes) exercise ≥6 h/week, and recreational athletes exercise ≥4 h/week (McKinney et al., 2019). Various sport types were included and based on the classification of Mitchell *et al.* (Mitchell, Haskell, Snell, & Van Camp, 2005). The different sport types were restricted to dynamic MVPA because these are the most practiced and common sports (Mitchell et al., 2005); 2) Type of study: peer-reviewed cross-sectional, prospective cohort studies or randomised controlled trials; 3) Primary outcome: sedentary time expressed in minutes per day and 4) Secondary outcome: light intensity physical activity (LIPA) and MVPA expressed in minutes per day and cardiometabolic health outcomes including physical fitness, exercise capacity, anthropometric measures (body weight, body mass index (BMI), waist circumference and percentage fat mass), systolic and diastolic blood pressure (BP), resting heart rate, lipid profile (blood total cholesterol, high-density lipoprotein (HDL) cholesterol, low-density lipoprotein (LDL) cholesterol and triglyceride concentrations) and the fasting glucose and insulin concentration.

2.3 Study selection

Studies were independently screened in three different steps by two authors (E.V. and E.C.). Firstly, duplicates were removed using the de-duplication method from Bramer *et al.* (Bramer, Giustini, de Jonge, Holland, & Bekhuis, 2016) and a first selection was performed based on titles and abstracts to identify relevant studies. Then, articles were screened and systematically excluded when they did not meet the pre-specified inclusion criteria. In addition, reviews, editorials and congress abstracts were also excluded. Disagreements between authors were resolved by consensus with a third reviewer (W.M.A.F).

2.4 Data extraction

Data were independently extracted by two of the reviewers (E.V. and E.C.). Data extraction was performed with the aid of a predesigned data collection form, adapted from the extraction form of the Cochrane Collaboration (Appendix S2). For each study, the reviewers extracted information with respect to study characteristics (type of study, population description and types of outcome measures); study participants (sample size and demographics); methods (study aim, study design, measurement methods, and number of included participants); outcome variables (outcome definition, unit of measurement, time points measured and reported, statistical method used). Continuous data including, means, standard deviations and the sample size numbers were extracted. Without availability of standard deviations, measures of variance were estimated from the standard error of a mean, confidence intervals or p-values according to the Cochrane Handbook for Systematic Reviews of Interventions the Cochrane Collaboration (Version 5.2, chapter 7) (Higgins & Green, 2017). In addition, if data were presented as median and interquartile range, the mean and standard deviation were estimated using the formula from Hozo *et al.* (Hozo, Djulbegovic, & Hozo, 2005).

2.5 Study quality assessment

The methodological quality of the included studies was independently assessed by two reviewers (W.M.A.F and E.V.) as recommended by Downs and Black (modified from Cochrane methodological quality assessment tool for non-randomized studies, the Cochrane Collaboration) (Downs & Black, 1998). Item four and eight were removed from the scale since they were not applicable for assessing observational studies. Here, the following methodological criteria were assessed based on 25 items distributed between five sub-scales: reporting (8 items), external validity (3 items), internal validity bias (7 items), internal validity confounding (6 items) and power (1 item) (Downs & Black, 1998). Each of these criteria were rated and classified as 'excellent' (score 22-26), 'good' (score 16-21), 'fair' (score 11-15) or 'poor' (score 11 or less) and provided an overall score to a maximum of 26 points (Downs & Black, 1998).

2.6 Statistical analysis

Data with regard to sedentary behaviour and PA were quantitatively summarized as mean and standard deviation. When the data were reported separately for sex (male vs. female) or days of the week (weekday vs. weekend day) these were combined according to the Cochrane Handbook for Systematic Reviews of Interventions the Cochrane Collaboration (Version 5.2, chapter 7). Sedentary behaviour and PA levels were compared with the average sitting time and PA levels of the general population reported by Van Dyck *et al.* (Van Dyck et al., 2015). In this observational multi-country cross-sectional study, PA and sedentary behaviour were objectively assessed in 5712 adults (aged 18-65 years) with the aid of ActiGraph accelerometers for seven consecutive days. For the meta-analysis only studies with individuals aged 18-45 years were included to reduce sample heterogeneity. Firstly, a good physiological function and cardiometabolic health is maintained until middle age and thereafter progressively deteriorates (McPhee et al., 2016). In addition, PA participation progressively declines with an increasing age and PA patterns will change due to the pensionable age in an older aged population (Rechel et al., 2013; Sun, Norman, & While, 2013).

Statistical analyses were performed using RevMan version 5.4.1 (Cochrane, London, United Kingdom). The mean differences (parameter athlete individuals – parameter general population) with 95% confidence intervals were calculated and pooled effect estimates were obtained using a random-effects model due to the large heterogeneity among the studies (different sport disciplines, age, sex and training volumes). Sensitivity analyses were performed to assess heterogeneity of the studies and to evaluate the robustness of the results. Each study was individually removed to evaluate the effect of that study on the summary estimates. Publication bias was assessed using funnel plots. The effect of heterogeneity of each summary effect size was quantified using a chi-squared test and the I^2 statistic, in which the boundary limits 25%, 50%, and 75% were designated as a low, moderate, and high heterogeneity value (Higgins, Thompson, Deeks, & Altman, 2003).

3. RESULTS

The search strategy identified 5029 potentially relevant studies from Pubmed (n=1868), Embase (n=2121), Web of Science (n=915) and CENTRAL (n=123), of which 3104 remained after deduplication (Figure 1). In addition, two additional hand-searched papers were included. Thirteen full-text articles fulfilled the inclusion criteria and were included in qualitative (n=13) and quantitative (n=11) synthesis (Table 1). Two studies were excluded from the quantitative analysis due to the higher age (>55 years, 63.4±4.6 years) of the individuals (McCracken & Dogra, 2018; Pollock, Duggal, Lazarus, Lord, & Harridge, 2018). Studies included were published over a 28-year period from 1991 to 2019. All studies were written in English and performed in eight different countries predominantly originating from Portugal (n=3). The studies included athletes from various disciplines including cross-country skiers (Alméras et al., 1991), university students with 9 different sports [cycling, hockey, kayaking, rugby, netball, athletics, water sports and rowing] (Clemente, Nikolaidis, Martins, & Mendes, 2016; Driller, Dixon, & Clark, 2017), triathlon (Drenowatz, Eisenmann, Pivarnik, Pfeiffer, & Carlson, 2013), cycling (Drenowatz et al., 2013; Pollock et al., 2018), running (Drenowatz et al., 2013; Exel, Mateus, Abrantes, Leite, & Sampaio, 2019; Rantalainen, Pesola, Quittner, Ridgers, & Belavy, 2018; Swartz, Miller, Cho, Welch, & Strath, 2017; Whitfield, Pettee Gabriel, & Kohl, 2014), football (Exel et al., 2019; Weiler, Aggio, Hamer, Taylor, & Kumar, 2015), elite athletes from different disciplines [long-distance running, road cycling, triathlon, judo, taekwondo, swimming, sailing, tennis, handball, track and field athletics and pentathlon] (Júdice, Silva, Magalhães, Matias, & Sardinha, 2014) and rowing (Sperlich et al., 2017). McCracken *et al.* only reported different sport categories which consisted of snow/ice, water, team, skill, racquet, multi, endurance, lifting, urban and others (McCracken & Dogra, 2018). All studies were performed during the active or competitive periods.

3.1 Study quality assessment

All studies scored between 12 and 19 points with a mean quality rating score of 15.9 (± 1.8), which indicates a moderate/good methodological quality. Five of the thirteen studies were considered to be of moderate (Alméras et al., 1991; Drenowatz et al., 2013; Rantalainen et al., 2018; Weiler et al., 2015; Whitfield et al., 2014) and eight of good methodological quality (Clemente et al., 2016; Driller et al., 2017; Exel et al., 2019; Júdice et al., 2014; McCracken & Dogra, 2018; Pollock et al., 2018; Sperlich et al., 2017; Swartz et al., 2017). The main sub-scales of methodological concerns among all studies were the internal (confounding) and external validity (Appendix S3). In all studies the reliability of the compliance with the interventions was unable to determine, whereas attempting to blind participants or researchers to the intervention they received or to their randomisation assignment was not reported. In addition, no adjustments were made for potential confounding variables in the analyses from which the main findings were. However, all studies reported the aims, main outcome measures, characteristics of the participants, the main findings and the point estimates of random variability. There was no evidence of data dredging, and all variables of sedentary behaviour and PA were measured in a valid and reliable way.

3.2 Study characteristics

The included studies were either cross-sectional studies (n=11) or prospective observational studies (n=2). The measurements of PA and sedentary behaviour within the prospective observational studies were performed during a low and high volume training week (Drenowatz et al., 2013) and for three months prior to running a marathon and three months after completing the marathon (Swartz et al., 2017). PA and sedentary behaviour were objectively measured using wearable technology including the Actigraph® accelerometer (Clemente et al., 2016; Exel et al., 2019; Pollock et al., 2018; Rantalainen et al., 2018; Swartz et al., 2017), Sensewear® armband (Drenowatz et al., 2013), Fitbit Flex® (Driller et al., 2017), Microsoft Band II (Sperlich & Holmberg, 2017) and the GENEActiv accelerometer (Weiler et al., 2015). In addition, four studies measured PA and sedentary behaviour in a subjective way with the aid of a three day activity record (Alméras et al., 1991), the International Physical Activity Questionnaire (Júdice et al., 2014; McCracken & Dogra, 2018; Whitfield et al., 2014) or the Multicontext Sitting Time Questionnaire (Whitfield et al., 2014).

3.3 Population characteristics

The included studies evaluated a total of 731 athletes with a mean age of 30.5±7.2 years (range: 20-35 years) and 40.3±16.4 years (range: 20-64 years) when the two studies with older athletes were included (McCracken & Dogra, 2018; Pollock et al., 2018), whereas one study did not provide information of the average study population age (Clemente et al., 2016). Overall, 52% (range: 22-67%) of the participants were male and six studies included only male participants. The athletes had a mean body height of 175.2±8.7cm and body weight of 72.8±11.3kg. The participants consisted of 7 cross-country skiers, 11 rowers, 38 football players, 322 joggers/runners, 125 cyclists and 213 athletes from different disciplines as described in the methods section. Ten studies reported the training volume of the athletes in various ways including minutes per day (86±42min/day; range: 44-147mi/day) (Alméras et al., 1991; Drenowatz et al., 2013; Júdice et al., 2014; McCracken & Dogra, 2018; Whitfield et al., 2014), kilometres per week (87±71km/week; range: 28-166km/week) (Pollock et al., 2018; Rantalainen et al., 2018) and training sessions per week (4±1 sessions per week; range: 3-5 sessions per week) (Clemente et al., 2016; Exel et al., 2019).

3.4 Physical activity and sedentary behaviour

All included studies reported data with respect to sedentary behaviour, expressed in minutes per day, and were included in the meta-analyses. Overall, the athletes (576±136min/day) spent significantly more time in sedentary behaviour (+79min/day; 95% confidence interval [CI]: [41, 65] min/day; $p<0.001$) compared to the general population (513±105min/day; Figure 2). With regard to PA, athlete individuals spent less time in LIPA (-92min/day; 95% CI: [-117, -66] min/day; $p<0.001$; Figure 3a) and had increased levels of MVPA (+62min/day; 95% CI: [38, 85] min/day; $p<0.001$; Figure 3b) compared to the general population (Appendix S4). However, these results were statistically heterogeneous with respect to the overall effect of sedentary behaviour (Q=321.6, $p<0.001$; I^2=96%) as well as the results from PA including LIPA (Q=84.7, $p<0.001$; I^2=89%) and MVPA (Q=320.1, $p<0.001$; I^2=97%). Visual inspection of the funnel plots revealed that effect sizes were symmetrically distributed, indicating that there was an absence of selection bias (Appendix S5). Older athletes spent less time in sedentary behaviour (490±80 min/day; n=204), whereas more time was spent in MVPA (146±67; n=204) compared to the younger individuals. In addition, no differences in sedentary time were found across different training volumes.

3.5 Associations between physical activity, sedentary behaviour and cardiometabolic health

Only two studies reported associations between sedentary behaviour, PA and cardiometabolic health related outcomes (Júdice et al., 2014; Pollock et al., 2018). Júdice *et al.* described the associations between sedentary behaviour and the main body composition variables within 82 male athletes from different disciplines (Júdice et al., 2014). They found that sedentary behaviour was positively associated with total and trunk adiposity, regardless of weekly training volume, age and residual mass. However, weight class sports (i.e. judo and taekwondo) were responsible for the most expressive association between sedentary behaviour and adiposity, compared to the non-weight sensitive sports or gravitational sports. In addition, Pollock *et al.* showed that sedentary time was not associated with any marker of cardiometabolic risk within recreational, non-elite cyclists (Pollock et al., 2018).

4. DISCUSSION

This review systematically evaluated sedentary behaviour and PA levels within athletes. In general, athletes exceeded the average sedentary time by almost 80 minutes per day, which make them even more sedentary compared to the general population. In addition, athletic individuals spent 1.5 hour less in LIPA, whereas one additional hour was spent in MVPA compared to the general population. These results suggest that athletes can be considered as both highly sedentary and highly active. This extents the existing concept of the active couch potato phenomenon in the general population, which describes individuals who meet the PA recommended guidelines but remain the rest of their waking hours sedentary (Healy et al., 2008; Owen, Healy, Matthews, & Dunstan, 2010). These results indicate that sitting time is not related to time spent in MVPA and that both sedentary behaviour and exercise are independent behaviour classes. Indeed, this study found that there was no association between sedentary time and training volume, and therefore confirmed the results of Whitfield *et al*. (Whitfield et al., 2014). This might indicate that MVPA is not simply replaced by sedentary behaviour and that more exercise does not automatically lead to a reduction in sedentary time. A possible reason for this can be a higher LIPA level in individuals with a lower training volume. This concept was already introduced by Craft *et al*. who included women meeting and exceeding the current PA recommendations for MVPA but still spent the majority of their waking time in sedentary behaviours (Craft et al., 2012). In fact, high amounts of MVPA may result in an increase in sedentary time due to a reduced drive to be physically active in off-training periods

(Puetz, 2006). Whitfield *et al.* showed that the majority of sedentary behaviour on workdays occurred in the context of working, reading or studying, while TV viewing was the primary contributor to nonworking days (Whitfield et al., 2014). This supports the idea that the workplace is a highly 'sedentarigenic' environment and, therefore, an important location to perform intervention strategies targeting prolonged sedentary time (Brierley, Chater, Smith, & Bailey, 2019; Chu et al., 2016).

Lifestyle factors are typically associated with increasing cardiometabolic risk, however, the extent to which this is due to PA and/or sedentary behaviour is unknown. Although a lot of studies have shown that prolonged sedentary time is independently related to impaired cardiometabolic health and all-cause mortality, even in individuals who meet the recommended PA guidelines (Katzmarzyk, Church, Craig, & Bouchard, 2009), the question that arises is whether high levels of MVPA can counteract the harmful effects of sedentary behaviour on cardiometabolic health. Recent population-based studies revealed a dose-response association between total sedentary time and cardiovascular disease or all-cause mortality risk, even in individuals who met the recommended PA guidelines. Interestingly, they also provided evidence that highly active individuals (60-75min of MVPA/day) seem to eliminate the risks associated with more than eight hours per day of total sitting time (Ekelund et al., 2016; Stamatakis et al., 2019). However, with TV-viewing time (>5h/day) the results were similar, except that high levels of MVPA only attenuate but not eliminate the increased risks. This may also apply to athlete individuals since the majority of their sedentary behaviour during nonworking days may be TV viewing. This often occurs in the evening after dinner, where prolonged postprandial sedentary behaviour may be particular detrimental for glucose and lipid metabolism (Benatti & Ried-Larsen, 2015). In addition, individuals who more frequently break their sedentary time during working hours compared to TV viewing will have more benefits with regard to cardiometabolic health (Benatti & Ried-Larsen, 2015). However, the association between sedentary behaviour, PA and all-cause mortality has only been reported with the aid of self-report questionnaires and a direct relation with cardiometabolic health has not been investigated so far. In this respect, it could be possible that there is a credible relation between objectively measured sedentary behaviour and cardiometabolic health in highly trained athletes. Although highly trained athletes are generally considered to be in good health, stratification by cardiorespiratory fitness (CRF) levels revealed considerable variability in cardiometabolic risk factors including high-density lipoprotein cholesterol and low-density lipoprotein cholesterol levels in male marathon runners (Ketelhut, Ketelhut, Messerli, & Badtke, 1996). In addition, La Gerche *et al.* showed an increased systolic blood pressure (147±14 mm Hg) among endurance athletes (La Gerche et al., 2012). Although it has been shown that there is a strong interrelationship between sedentary time, MVPA and CRF, these factors possibly also have an independent association with cardiometabolic health (Greer, Sui, Maslow, Greer, & Blair, 2015). Therefore, when evaluating the association between sedentary behaviour, MVPA and cardiometabolic health, CRF should also be considered, especially within athletes. Although it is important to mention that both sedentary behaviour and MPVA are behaviours, whereas CRF is a physiological measure reflecting a combination of genetic potential, behavioural and functional health of various organ systems (Carnethon et al., 2010), several studies have reported that CRF has a marked effect on cardiometabolic health (Knaeps et al., 2016). In addition, it has been shown that there is an inverse association between high sedentary time and a lower CRF (Kulinski et al., 2014; Prince, Blanchard, Grace, & Reid, 2016), implying that the association between sedentary behaviour and cardiometabolic health may be partly mediated through a lower CRF (Knaeps et al., 2018). Nevertheless, van der Velde *et al*. showed that even individuals with high CRF may be at increased risk for metabolic diseases due to prolonged sitting and that both sedentary time and CRF were independently associated with the metabolic syndrome and type 2 diabetes mellitus (van der Velde et al., 2018). However, this study was performed in the general population in which parameters of CRF were lower compared to athletic populations. Indeed, approximately 30% of CRF can be explained by factors other than PA, which means that regular engagement in MVPA will not necessarily lead to an increased CRF and high levels of CRF are not always due to frequently engaging in MVPA (Després, 2016). Therefore, although sedentary behaviour, MVPA and CRF are interrelated to each other, they should be considered as different factors that are independently associated with cardiometabolic health (Després, 2016).

Zheng *et al.* showed that total sedentary time and prolonged sedentary bouts were positively associated with cardiometabolic health in physically active (>1 hour/day of MVPA) young male adults (Zheng et al., 2021). This association was partly found in our systematic review by Júdice *et al.* who found an association between sedentary behaviour and the main body composition variables within 82 male athletes from different disciplines. They included athletes with various levels of sedentary behaviour (120-900 min/day), and as expected they found that sedentary time predicted some of the total and regional fat mass in an athletic population, regardless of their weekly training volume and indicates a similarity to what occurs in the general population (Júdice et al., 2014). However, this association was only significant for weight class sports including judo and taekwondo that simultaneously presented more time spent in sedentary behaviour and had lower weekly training volumes compared to other sport disciplines. This association is somewhat surprising because these athletes have a remarkably higher daily PA that far exceeds the recommendations for the general population and should normally be enough to maintain an excellent body composition profile. However, these individuals are able to spend more time in sedentary behaviour, which could be the reason for the association between PA levels and adiposity. Although in the general population it is known that an increased adipose tissue mass is independently related to an impaired cardiometabolic risk profile, it remains unclear whether this independent relationship still exists within athletes. On the other hand, athletic individuals with substantial higher training volumes may compensate for the increased time spent in sedentary behaviours to offset the negative effects of inactivity and thereby prevent any association between sedentary behaviour and cardiometabolic health. Nevertheless, it has been shown that, even in active individuals, both glycaemic control, lipid metabolism and skeletal muscle blood flow are affected due to sedentary behaviour and lack of PA (Bergouignan et al., 2009; Stephens, Granados, Zderic, Hamilton, & Braun, 2011; Wagenmakers, Strauss, Shepherd, Keske, & Cocks, 2016). In contrast, Pollock *et al.* only found an independent association between CRF and cardiometabolic health in amateur cyclists of older age (Pollock et al., 2018). However, there was a greater variability in training volume compared to levels of MVPA and sedentary behaviour. Therefore, it is recommended to include individuals with relatively wide ranges of sedentary behaviour and high levels of MVPA in future studies. In addition, no measurements of LIPA or total PA were included, which could be a possible reason why no associations were found between sedentary time and cardiometabolic markers. In older adults in could be the case that they will frequently interrupt their sedentary time with LIPA and subsequently improve cardiometabolic health. A recent systematic review of Chastin *et al.* showed that, in mainly inactive adults, short but frequent bouts of LIPA throughout the day reduced postprandial glucose and insulin levels compared with continuous sitting, whereas some intervention studies reported reduced adiposity, improved blood pressure and lipidaemia (Chastin et al., 2019). Although the current knowledge with regard to physiological adaptations to LIPA as a recovery strategy in athletes has not been fully elucidated, replacing sedentary time with LIPA could be a promising approach to improve or optimize cardiometabolic health (Chastin et al., 2019; Duvivier et al., 2013). In this case, frequent interruptions of sedentary behaviour with LIPA can both counteract the adverse effects of prolonged sitting and promote the positive effects of active recovery (Ortiz, Sinclair Elder,

Elder, & Dawes, 2019). This suggests that promoting a better balance between sedentary behaviour and LIPA may determine a healthier cardiometabolic profile, even in elite athletes. However, for further research it is recommended to unravel the associations between sedentary behaviour and cardiometabolic health in these athlete populations using reliable and standardized methods.

Several limitations of the included studies were observed. First, studies with relatively small sample sizes, heterogeneous study populations which consisted of multiple sport disciplines, different measurement instruments and their settings, as well as data processing procedures were included into the meta-analysis. In addition, only one study distinguished sedentary behaviour and PA levels based on sex. This impedes the comparison and generalization of the results and the independent contribution of sex differences and any of these different sports is difficult to establish and should be further investigated. This may explain the high heterogeneity of the primary and secondary outcome measures. However, since clinical and methodological diversity is always present in meta-analysis, statistical heterogeneity is inevitable. Moreover, Higgens *et al*. reported that almost one third of meta-analyses have moderate to considerable heterogeneity (Higgins et al., 2003). Second, only two studies evaluated sedentary behaviour and PA levels in combination with one or more of the cardiometabolic risk factors. In this way, no direct associations between sedentary behaviour, PA and cardiometabolic risk factors could be made and no cut-off values to improve cardiometabolic health could be determined. In addition, most included studies had a cross-sectional study design which makes it difficult to establish causal relationships. Moreover, there are no studies that attempted to improve cardiometabolic heath by means of manipulating the off-training PA behaviours while awake. Therefore, it is recommended in future research to include more prospective cohort studies and randomised controlled trials. Furhtermore, sedentary behaviour was mainly based on subjective quantification or on objective measurements with the Actigraph® accelerometer. Subjective measures using questionnaires often have low responsiveness and criterion validity (Chastin, Culhane, & Dall, 2014) and underestimate sedentary time with approximately two hours per day (Prince et al., 2020). In addition, while the Actigraph® accelerometer is a widely used measurement tool, it is not designed to accurately measure postures like sitting and standing. Recent findings have raised concerns about how well this device actually measures sitting duration (Kozey-Keadle, Libertine, Lyden, Staudenmayer, & Freedson, 2011). Therefore, it is higly recommended to use PA monitors which utilizes both accelerometer and inclinometer functions for future studies. This device has been validated for the measurement of common PA and sedentary behaviours such as sitting, standing, and walking (Grant, Ryan, Tigbe, & Granat, 2006; Kozey-Keadle et al., 2011; Ryan, Grant, Tigbe, & Granat, 2006).

In conclusion, the present results suggest that athletes exceeded the average time spent sedentary per day. As such, they are more sedentary compared to the general population. However, whether the negative effects of sedentary behaviour can be eliminated by the high amounts of MVPA in athletes still needs to be elucidated.

Figures

Figure 1; Flow diagram of the study selection process

Figure 2; Forest plot of mean differences of sedentary time within athletes, compared to the general population. Abbreviations: CI: confidence interval, I2: the variation in pooled effect size attributable to heterogeneity within that group.

Figure 3; Forest plot of mean differences of light intensity physical activity (a) and moderate-to-vigorous physical activity (b) within athletes, compared to the general population. Abbreviations: CI: confidence interval, I2: the variation in pooled effect size attributable to heterogeneity within that group, LIPA: light intensity physical activity, MVPA: moderate-to-vigorous physical activity.

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