Health, Wellness and Cognitive Performance Benefits of Tennis

Mark Kovacs, Babette Pluim, Jack Groppel, Miguel Crespo, E. Paul Roetert, Brian Hainline, Stuart Miller, Machar Reid, Bernard Pestre, Max De Vylder, Nicola A. Dunn, Dave Miley, Tim Jones

ABSTRACT

Background/Aim: *Tennis is a sport played in nearly every country and is one of the top participation sports in the world. It is considered a sport for a lifetime due to the ability to play from a very young age to very late in life. As global society is facing more physical inactivity, increases in many preventable diseases, limited funding from private and public sources for physical activity, it is important to understand the many health, wellness and cognitive performance benefits of tennis. Methods: This review focuses on the health, cognitive and wellness aspects of tennis play in different population groups. Results: Tennis participation provides positive health benefits on aerobic capacity, body fat, morbidity, mortality, blood pressure, cholesterol, diabetes, obesity, and bone health. Conclusions: Regular participation in tennis play provides a multitude of health, cognitive and wellness benefits from a young age to late in life.*

Key Words: *Aging, Children's health and exercise, Exercise, Health promotion through physical activity*

INTRODUCTION

Tennis is one of the most popular sports throughout the world and is played by millions of people. One great benefit of tennis is that many people who play tennis maintain the sport throughout life (as can been seen by competitions organized for individuals over the age 80 and even some countries have national championships in the 90 and over age group[1]). In 2007 and 2009 two reviews were published looking at the health benefits of tennis[2,3] and in 2006 a review focused specifically on the health benefits of veteran (senior) players[4]. In 2013, the International Tennis Federation (the world governing body of tennis) established the Health Benefits of Tennis Taskforce to help increase awareness of the health, wellness and cognitive performance benefits of tennis participation and to develop materials to help bring greater understanding around the many health benefits of playing tennis. The purpose of this review is to highlight the relevant research surrounding these benefits.

CURRENT PUBLIC HEALTH RECOMMENDATIONS & CONSEQUENCES OF PHYSICAL INACTIVITY

Men and women of all ages, socioeconomic groups, and ethnicities are recommended to undertake at least 150 minutes per week of moderate-intensity aerobic physical activity, such as brisk walking[5]. Muscular strengthening physical activities are also recommended for health improvement[5]. Physical activity was recently considered a cornerstone for combating noncommunicable diseases by the United Nations[6]. The World Health Organization (WHO) recognizes physical inactivity as one of the leading global risk factors for morbidity and premature mortality[7]. The WHO estimates that four of every five adolescents aged 13–15 years do not meet present physical activity guidelines. These adolescents are at increased risk of coronary heart disease, diabetes, some types of cancer, and premature death[8]. In 2011 the

WHO recognized physical inactivity as one of the leading global risk factors for morbidity and premature mortality[7]. Compared with inactive individuals, those who were active (about 1.5h per week) lived 3 years longer[9]. The American College of Sports Medicine and the American Heart Association recommend that to promote and maintain health, adults aged 18 to 65 years should partake in a minimum of 150 minutes per week (ie, 30 minutes for 5 days) of moderate-intensity physical activity as well as at least 2 days per week of muscle-strengthening activities that work the major muscle groups[10].

THE HEALTH RELATED BENEFITS OF TENNIS

Tennis, as an exercise form, is one of the best examples of intermittent moderate/high intensity exercise. In a review of heart rate measurements in tennis players it was found that mean (SD) heart rate during singles play ranged from 141 (SD+16) to 182 (SD¬+12) beats/minute, equating to 70–90% of maximum heart rate[2]. Mean oxygen consumption (VO_2) during play ranged from 23.1 (SD +3.1) to 40.3 (SD+5.7) ml/kg/min, reflecting 50% to 80% of VO_2max[2]. As a result, tennis singles play can be categorized as a vigorous intensity exercise (>6 METS)[2].

While low intensity activities (<4 METs) were not associated with reduced mortality rates, moderate activities (4 – <6 METs) appeared somewhat beneficial, and vigorous activities (≥6 METs), such as tennis, clearly predicted lower mortality rates[11]. As a moderate or vigorous activity, tennis offers greater protection from physical impairment and mortality than does moderate activity[12].

High Intensity Interval Training (HIIT) involves short periods of intense exercise interspersed with periods of recovery involving lower intensity exercise and has become a major area of research over the past few years[13 14]. HIIT training describes a wide variety of work:rest ratios, from as little as 6 seconds of work to as long as 4 minutes with different length rest periods. In a recent review it was found that HIIT promotes superior improvements in aerobic fitness and similar improvements in some cardiometabolic risk factors in comparison to Continuous Moderate Exercise (CME), when performed by healthy subjects or clinical patients for at least 8–12 weeks[15]. For a more in-depth review of HIIT see[13 14]. In tennis, it has been reported that HIIT as well as Repeated Sprints Training (RST) generate improvement in general aerobic fitness. HIIT i.e., 3x (3 × 90 seconds), 90–95% HRmax, with 3-minute rest between each set), induced greater improvements in tennis-specific endurance than RST i.e., 3x (10×5-second) shuttle sprints, with 20-second rest between repetitions, 3 minutes between sets[16]. Although more research is still needed in this area over longer periods with work:rest ratios that more closely represent tennis play, these findings lend support to the benefits of typical tennis play. As the work to rest ratios in tennis range between 1:2–1:5 during matches[17], future research should focus on HIIT with these similar ratios. Like most exercise forms, tennis does have a potential risk of injury, and this should be assessed before starting any new physical activity program to allow for appropriate and progressive volume and intensity changes.

AEROBIC CAPACITY

Tennis players have been reported to have a wide range of mean VO_2 max values [2 17–20]. These ranges are due to factors such as gender, age and training level. Despite these differences, tennis players have higher levels of aerobic fitness compared with normative data for active controls of the same age and gender[21 22]. In a longitudinal study, sedentary, middle aged volunteers who exercised three times a week for 30 minutes per session for 20 weeks found that tennis produced increases in endurance capacity (5.7%), compared with no change for the control group[23]. This was despite the duration of each training session being only 30–50% of a typical tennis practice or match session. Although many studies have shown aerobic capacity improvements using exercise modalities, intensities, and work:rest ratios that are similar to tennis, a paucity of research currently exists looking specifically at the influence of consistent tennis play on changes in aerobic capacity.

AGING AND PARTICIPATION

Although there is clear evidence that regular physical activity has powerful positive health and fitness effects[24], most middle-aged to elderly people are classified as sedentary. For example, only 25% of adults in the United States report engaging in the recommended amounts of physical activity (i.e., 30 minutes of moderate-intensity activity on 5 or more days per week, or 20 minutes of vigorous-intensity activity on 3 or more days per week), while 29% report engaging in no leisure-time regular physical activity[25]. This lack of physical activity, in combination with poor diet are the major causes of an epidemic of obesity that is affecting the elderly as well as middle-aged and younger populations[25]. Data from a study of 9,704 middle-aged and elderly women showed that any increase in physical activity is beneficial[26]. Tennis provides a unique combination of benefits to the older population in addition to the physical benefits (which many of exercise modalities may not be able to offer) such as strategy, hand-eye co-ordination, reactions to multiple different stimuli, varied scenarios/conditions, competition, and social interactions with opponents and doubles partners. As the population continues to age, more work should be performed evaluating the effect of tennis participation in these populations.

REDUCED MORBIDITY

A longitudinal study of 1,019 male medical students' physical activities between 1948 and 1964 with a follow-up between 22 and 40 years later found that individuals who rated tennis as a sport in which they had relatively high ability and played during medical school was associated with a lower risk of cardiovascular disease in later life. After adjustment for confounding variables, the relative risk of developing cardiovascular disease was 0.56 (95% confidence interval, 0.35–0.89) in the high tennis ability group and 0.67 (0.47–0.96) in the low tennis ability group, compared with the no ability group[27]. One likely reason for this beneficial health outcome is that tennis was the sport most often played throughout the mid-life years. Many of the other sports (American football, baseball and basketball) that individuals participated in during medical school were not an activity that they continued throughout their life[27].

REDUCED MORTALITY RISK

It is well understood that lack of physical fitness contributes to premature death. The highest all-cause death rate in a prospective study of 9,777 men was in individuals who were unfit, while the lowest death rate was in men who were physically fit[28]. Compared with being inactive, achievement of activity levels that approximate the recommendations for moderate activity was associated with a 27% and 32% decreased mortality risk, respectively[29]. This was also confirmed in one of the landmark studies by Paffenbarger et al (1993) which showed that tennis, as well as other similar forms of exercise, results in lower premature mortality rates[30]. Even with a reduction in total time of exercise, vigorous-intensity is associated with a decrease in mortality risk. This lends significant support to tennis play (and specifically singles play) as a highly desirable activity as it is considered vigorous exercise[2], and most individuals typically play tennis between 60–120 minutes due to the length of matches and available court time.

A prospective questionnaire-based study examined the association between recreational physical activity and mortality in middle-aged and older women and measured levels of physical activity via a questionnaire in 1980 that was updated every 2 to 4 years between 1980 and 1996[31]. The authors examined physical activity in hours per week rather than in metabolic equivalent task units (METs). Physical activity duration was found to be inversely associated with mortality risk[31].

A prospective study of postmenopausal women found a consistent, graded, inverse association between frequency of leisure physical activity and total mortality[32]. Women in the highest level of physical activity had approximately 30% lower risk of death, compared with those in the lowest level. In this study, playing tennis was considered one of the best physical activity exercises to lower the risk of death[32]. In a separate study, it was found that males who became inactive had a 72% increased risk of mortality compared with men who remained active, and that their risk did not differ significantly from that of men who remained inactive. This study confirmed the hypothesis that decreased physical activity might be associated with increased mortality risk[33]. Such data highlight the need to perform activities that can be performed throughout life and lends support to activities that are able to be performed into old age. As tennis has structured competitions that in many countries include a national championships from as young as 12 and under to individuals who are 90 years and older[1], it is one of the few sports that can realistically be performed into old age. Although some debate exists as what is optimum intensity during exercise and how different levels of exercise (low, moderate, high, vigorous etc) contribute to mortality rates, it is clear that less active individuals are at a higher risk of premature mortality than active individuals into old age[33 34]. Becoming or remaining sedentary was significantly associated with increased mortality risk in comparison with remaining physically active[33]. A study comparing elite male tennis players (40 to 60+ years of age) with active age-matched controls reported that the tennis players expended more energy during recreation, work, and exercise, engaged in more vigorous activity, and consequently scored significantly higher on the Yale Physical Activity Survey[35]. This suggests that tennis players are more active in other activities throughout the day that also aids in the reduction of mortality risk above and beyond just the exercise performed during tennis play.

BLOOD PRESSURE

Although few studies of blood pressure in tennis players have been performed, one such study showed that tennis play provided similar benefits in blood pressure readings between senior male tennis players and moderately active age matched controls[35]. Women who performed even small to moderate amounts of physical activity (2–12 times per month, 0.5–2 hours per week) and of moderate-to-vigorous activity (≥5kcal/kg/h) had significantly lower systolic blood pressure (-1.8%) values than sedentary women[36]. The researchers concluded that habitual physical activity in older women is associated with the clinically important benefit of lower systolic and diastolic blood pressures, and that this benefit is independent of physical activity-related changes in obesity and plasma insulin[37]. In a recent study comparing tennis players to weightlifters and non-trained volunteers, systolic blood pressure differed significantly among the three study groups, independently of age, body mass index (BMI), frequency, duration and intensity of exercise. Flow-mediated dilation was significantly lower in weightlifters than tennis players, while mean carotid intima-media thickness (IMT)—widely used in observational studies and trials as an

intermediate or proxy end point for cardiovascular disease—was significantly higher in weightlifters as compared to tennis players and the control group. Tennis play showed a positive response to endothelial function[38].

DIABETES

As far back as 1926, tennis has been shown to help reduce insulin needs in diabetics as well as blood sugar levels[9]. More recently, a study of 12 tennis players with Type II diabetes, who performed 90 minutes of tennis play twice a week for six weeks, showed a reduction (SD) in mean glucose concentration from 188.0 (72.7) mg/dl at baseline to 156.7 (52.2) mg/dl after the 6 weeks of training[40] —nearly a 20% reduction. This study included beginner tennis players who participated twice a week with a modified ball for six weeks. Future studies should investigate the effects of a similar protocol extended over months or years on individuals with Type II diabetes.

CHOLESTEROL

When matched for age, sex and education, tennis players compared favorably to sedentary controls in having significantly higher high density lipoprotein (HDL) cholesterol—men, 1.39 (0.30) v 1.17 (0.31) mmol/l; women, 1.72 (0.22) v 1.56 (0.29) mmol/l [41]. However, not all studies show a greater improvement in cholesterol when compared to appropriately matched controls[35]. The higher HDL cholesterol concentrations associated with a lower risk of cardiovascular disease implies that individuals who play tennis may be at a reduced risk of cardiovascular events[42]. Compared to sedentary individuals, physically active women had significantly lower levels of total serum cholesterol, LDL and oxidized LDL cholesterol, triglycerides, apolipoprotein B, and higher levels of HDL cholesterol and apolipoprotein A1[43]. When comparing cholesterol levels of tennis players to sedentary individuals, the tennis players compare favorably. However, more research needs to look at long-term tennis play and changes in cholesterol over time.

BODY COMPOSITION

The rising prevalence of obesity worldwide is a major global health concern. This rise is due in part to sedentary behavior, and exercise is one of the most promoted and recommended activities to combat obesity[44]. Tennis has been shown to be an excellent way of burning calories and specifically reducing fat mass. Young adult tennis players engaged in singles play could expend between 7.8 and 10.1 kcal/min[45 46]. Similar results were found for senior athletes[47]. Increased mortality has been observed with weight gain[48]. Fitness and body mass index were strong, and independent predictors of all-cause mortality in adults 60 years or older[49]. Tennis is an effective form of physical activity that has been shown to limit excess body fat[36], and male and female tennis players have been reported to have below-average body fat compared with normal controls [41 50–52]. Tennis players had 3–4% less body fat than appropriately matched controls[50 52]. It has also been shown that elite level competitive tennis players aged over 40 are more physically active throughout the day than matched controls[35]. This potential carry-over influence of tennis play, on a more active daily life (or individuals who are more active are more likely to play tennis) is another benefit that may contribute to lower body fat percentages in tennis athletes.

BONE HEALTH

Bone health has been well researched in tennis players. Over two dozen studies have analyzed bone health in tennis players at many different levels. Some of the major findings that were well summarized by Pluim et al (2007) showed that bone mineral content (BMC) and bone density (BMD) were consistently greater in the dominant arm compared with the non-dominant arm of the tennis player. This finding is consistent with the increased loading that occurs on the dominant arm compared to the non-dominant arm as a result of repeated ball contacts. Also, BMC and BMD were greater in the hip and lumbar spine of tennis athletes compared to controls[2]. Some more recent research on elite youth tennis athletes supports a strong influence of muscular action on bone adaptation. The researchers suggest factors other than local muscle size also contribute to bone strength[53]. BMC, bone area and lean mass in dominant arm has been shown to be related to the number of weekly hours devoted to tennis[54]. The exercise-induced change in muscle cross-sectional area was predictive of BMC in prepubertal and peripubertal tennis players. Both pre/peri- and postmenarcheal tennis players showed significant exercise-induced skeletal benefits within a year, with greater benefits in cortical bone geometry in pre/perimenarcheal girls[55]. As long-term bone health is a major concern in the female population, participation in tennis at a young age should be considered to aid in the development strong bone health. It is interesting to note that the same research group[56] found a different response to loading in young boys compared to the findings in young girls. The osteogenic response to loading was greater in peri- compared with pre-pubertal boys[56], which was in contrast to their findings in girls[55]. The authors suggested the difference may be caused by differences in training history and that the windows of opportunity to improve bone mass and size through exercise may be longer in boys than in girls[56]. Playing tennis before during and immediately after puberty has direct benefits to bone growth, but long term tennis play in adulthood also shows benefits and continued improvements in bone health[57]. BMD during pregnancy typically are decreased and although limited research is available on tennis play during pregnancy, one study has shown that individuals who participate in tennis play during pregnancy had less of a reduction in BMD than

individuals who did not play tennis[58]. This initial study suggests that tennis participation during pregnancy may be advisable from a bone health perspective. It is recommended that the individual would be accustomed to tennis prior to pregnancy[59]. In summary, playing tennis leads to healthier bone structure in both genders and across the age spectrum. This conclusion supports the exercise recommendations in the "Physical activity and bone health" position stand produced by the American College of Sports Medicine (ACSM)[60]. For more in-depth analysis of bone health studies in tennis please refer to Pluim et al (2007).

COGNITIVE PERFORMANCE

Research has demonstrated that physical activity can slow down or prevent functional decline associated with aging while improving health in older individuals[61 62]. Evidence for connections between physical activity and brain biology is significant[63–72]. It has been shown that older tennis athletes' performance on simple, choice, and movement time tasks were substantially better than the older sedentary adults[73]. Smaller benefits were observed for young adults. Similar results (i.e. better performance by older high-fit than older low-fit individuals), have been found in a large number of cross-sectional studies—see[74] for a review. A growing body of literature indicates that physical activity is associated with improvements in brain function and cognition during childhood and through adulthood[75–80]. Individuals who play tennis show evidence of increased cerebral activity with eye movement tracking[81], along with improved stress reduction[82]. In another study it was reported that older active men were able to react to stimuli and move their forearms as quickly as young sedentary men[83]. Young and old tennis players have shown to have significantly quicker reaction times than their non-active age matched peers[84]. In a more recent study, similar findings have been shown (better reaction times) when comparing tennis players to swimmers or sedentary controls[85]. The researchers concluded that tennis athletes had superior temporal processing[85]. Tennis players have also been shown to have superior capabilities in motion detection, speed discrimination, and backward masking compared to triathletes or non-athletes[86]. Speed processing and temporal processing is often faster and more accurate in tennis players[86]. The researchers also indicated that tennis players perform better in general than triathletes and non-athletes under conditions of strong time limitations[86]. This would be expected due to the differences in the type of activities and training differences.

WELLBEING & REDUCTION IN PSYCHOLOGICAL DISTRESS

Strong associations exist between physical activity levels and levels of psychological distress[87]. Mental health benefits occur when individuals exercise at least 20 min/week, although a dose-response pattern with greater risk reduction is apparent at a higher volume and/or intensity[87]. Tennis players (male and female) have a reduced likelihood of psychological distress compared to lower volume and lower intensity types of exercise[87]. Young tennis players perceived greater autonomy due to the ability to use effective coping strategies such as active planning, cognitive restructuring, emotional calmness and seeking of social support[88]. Results in this study confirmed also that the greater perceived autonomy was explaining athletes high levels of psychological well-being[88].

Engaging in physical and leisure activities affects not only cognitive function but also emotional satisfaction and quality of life[89]. The association between exercise participation and well-being was assessed in approximately 8,000 adults aged 18 to 65 years from the Netherlands Twin Registry. Exercisers were more satisfied with their life and happier than non-exercisers at all ages[89]. However, more research is needed specifically looking at tennis participation in this area.

Table 1: A Sampling of Overall Benefits of Tennis Participation In Addition To Typical Health Benefits

A non-collision sport
A great way to meet people and spend time with friends
Suitable for all ages and skill levels
A game that can be started at any age
A game that can be played for a lifetime
Played in nearly every country in the world
Gives a total body workout
Has built in rest periods
Involves cognitive function (strategy, tactics, reaction time, coordination)
Provides low lactic acid buildup, resulting in low levels of perceived exertion

*List compiled by members of the ITF Health Benefits of Tennis Taskforce

Table 2: Potential Benefits of Consistent Participation in Tennis

Increased Aerobic Capacities [23, 35, 41, 91, 92]
Lower Resting Heart Rate and Blood Pressure [41]
Increased Bone Density [2]
Improved Reaction Times [93]
Lower Body Fat [35, 41, 94]
Improved Muscle Tone, Strength & Flexibility [35, 41, 92]
Increased Reaction Times [73, 77, 95]
Reduced Stress [87]
Lower Cardiovascular Risk & Mortality Rates [27, 30]

LIMITATIONS AND FUTURE RESEARCH

Most tennis studies involve small sample sizes, very few are longitudinal in nature and there is the potential for selection bias. Also, it must be noted that in most parts of the world tennis is associated with higher socioeconomic status. Most early tennis studies attributing positive health benefits to tennis participation have been limited because of their inability to control for various confounding factors[4]. Due to these limitations future research is needed with larger samples, such as longitudinal and prospective studies in youth and older adults. As the population ages in most Western countries, more research is needed in older tennis athletes, especially how degrees of participation affects various health, fitness, and cognitive functions in older adults new to the sport of tennis.

SUMMARY AND CONCLUSIONS

As tennis is one of the most popular sports worldwide, and can be performed throughout an entire lifespan, it is one of very few physical activities that can be recommended to nearly all individuals who wish to participate in sport for life due to the numerous benefits (see *Table 1*). The purpose of this article was to highlight the many studies that have linked tennis to better health, wellness and cognitive performance markers in youth, adult and senior populations. Additionally, some salient features of improving societal health through tennis participation are discussed. It is well understood that personal investment, enjoyment, involvement opportunities, and social support are significant predictors of commitment to ongoing tennis participation, and this commitment significantly predicts participation frequency[90]. This is an important finding, as much of the challenge in improving health metrics in society lies in the continuation of exercise habits and behaviors. Playing tennis contributes to increased aerobic capacity, lower resting heart rate and blood pressure, improved metabolic function, increased bone density, lower body fat, improved muscle tone, greater strength and flexibility, and improved reaction times and overall cognitive function (*Table 2*). All of this occurs while decreasing stress in an environment that promotes social interaction and it is a sport that can be performed at any age and for a lifetime. Pluim et al (2007) stated that "based on the scientific evidence available, it is difficult to find an activity that offers as wide a range of overall health benefits as tennis, and individuals who take up tennis reap tremendous rewards." The authors of this review support the findings of Pluim et al (2007), and feel that from the available research, tennis should be considered one of the priority exercise forms recommended by healthcare professionals, government agencies and other groups who are involved in helping to improve the health, cognitive, and wellness status of society.

SUMMARY BOX

- *Tennis is one of the largest participation sports worldwide and can be played from a very young age to old age. To highlight this many countries have national championships for the 10 and under age group to the 90 and over age group.*
- *Tennis participation on a regular basis can improve aerobic capacity, lower resting heart rate and blood pressure, increase bone density, increase reaction time, improve strength and flexibility, lower body fat, lower cardiovascular risk and mortality risk.*
- *Tennis participation provides many benefits in addition to the physical parameters including cognitive and wellness benefits.*

Contributor Statement MK, BP, JG, MC, EPR, BH, SM, MR, BP, MDV, NAD, DM, TJ all contributed to the planning, recording and reporting of the manuscript. MK serves as the guarantor.

Funding No funding provided for this manuscript

Conflict of Interest No conflict of interest

References

1. USTA. USTA Adult and Senior Competition. http://www.usta.com/Adult-Tennis/USTA-Adult-Senior-Tournaments/ 2013.
2. Pluim BM, Staal JB, Marks BL, et al. Health benefits of tennis. *Br J Sports Med* 2007;41(11):760–68.
3. Groppel J, DiNubile N. Tennis: For the health of it! *Phys Sportsmed* 2009;37(2):40–50.
4. Marks BL. Health benefits for veteran (senior) tennis players. *Br J Sports Med* 2006;40:469–76.
5. Physical, Activity, Guidelines, et al. Physical Activity Guidelines Advisory Committee Report. Washington, DC: US Department of Health and Human Services, 2008.
6. UN. United Nations high-level meeting on noncommunicable disease prevention and control. New York, NY: United Nations General Assembly, 2011.
7. WHO. Physical inactivity: a global public health problem. Geneva, Switzerland: World Health Organization, 2011.
8. Lee I-M, Shiroma EJ, Lobelo F, et al. Effect of physical inactivity on major non-communicable diseases worldwide: an analysis of burden of disease and life expectancy. *The Lancet* 2012;6736(12):61031–39.
9. Mountjoy M, Andersen LB, Armstrong N, et al. International Olympic Committee consensus statement on the health and fitness of young people through physical activity and sport. *Br J Sports Med* 2011;839-848:839–48.

10. Haskell WL, Lee IM, Pate RR, et al. Physical activity and public health: Updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. *Med Sci Sports Exerc* 2007;39(8):1423–34.
11. Lee I, Hsieh C, Paffenbarger R. Exercise intensity ad longevity in men: The Harvard alumni health study. *JAMA* 1995;273:1179–84.
12. Simonsick E, Lafferty M, Phillips C, et al. Risk due to inactivity in physically capable older adults. Am J Public Health 1993;83:1443–50.
13. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: part I: cardiopulmonary emphasis. *Sports Med* 2013;43(5):313–38.
14. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle. Part II: anaerobic energy, neuromuscular load and practical applications. *Sports Med* 2013;43(10):927–54.
15. Kessler HS, Sisson SB, Short KR. The potential for high-intensity interval training to reduce cardiometabolic disease risk. *Sports Med* 2012;42(1):489–509.
16. Fernandez-Fernandez J, Zimek J, Wiewelhove T, et al. High-intensity interval training vs repeated sprint training in tennis. *J Strength Cond Res* 2012;26(1):53–62.
17. Kovacs M. Applied physiology of tennis performance. *Br J Sports Med* 2006;40:381–86.
18. Kovacs M, Chandler WB, Chandler TJ. *Tennis training: enhancing on-court performance*. Vista, CA: Racquet Tech Publishing, 2007.
19. Kovacs MS. Tennis physiology: Training the competitive athlete. *Sports Med* 2007;37(3):189–98.
20. Kovacs MS, Pritchett R, Wickwire PJ, et al. Physical performance changes in NCAA division I tennis players after the unsupervised break between fall and spring semester. *Br J Sports Med* 2006;41:705–10.
21. Jackson AS, Beard EF, Wier LT, et al. Changes in aerobic power of men, ages 25-70 yr. *Med Sci Sports Exerc* 1995;27:113-20.
22. Jackson AS, Beard EF, Wier LT, et al. Changes in aerobic power of women, ages 20-64 yr. *Med Sci Sports Exerc* 1996;28:884–91.
23. Wilmore JH, Davis JA, O'Brien R, et al. Physiological alterations consequent to 20-week conditioning programs of bicycling, tennis, and jogging. *Med Sci Sports Exerc* 1980;12:1–8.
24. Chodzko-Zajko WJ, Proctor DN, Fiatarone Singh MA, et al. Exercise and physical activity for older adults. *Medicine and Science in Sports and Exercise* 2009;41(7):1510–30.
25. Kahn E, Ramsey L, Brownson R, et al. The effectiveness of interventions to increase physical activity. *Am J Prev Med* 2002;22:73–107.
26. Gregg E, Cauley J, Stone K, et al. Relationship of changes in physical activity and mortality among older women. *JAMA* 2003;289:2379–86.
27. Houston TK, Meoni LA, Ford DE, et al. Sports ability in young men and the incidence of cardiovascular disease. *Am J Med* 2002;112:689–95.
28. Blair SN, Kohl HW, Barlow CE, et al. Changes in physical fitness and all-cause mortality. *JAMA* 1996;273(14):1093–98.
29. Leitzmann M, Park Y, Blair A, et al. Physical activity recommendations and decreased risk of mortality. *Arch Intern Med* 2007;167(22):2453–60.
30. Paffenbarger RS, Hyde RT, Wing AL, et al. The association of changes in physical-activity level and other lifestyle characteristics with mortality among men. *N Engl J Med* 1993;328(8):538–45.
31. Rockhill B, Willett W, Manson J, et al. Physical activity and mortality: A prospective study among women. *Am J Public Health* 2001;91:578–83
32. Kushi L, Fee R, Aaron F, et al. Physical activity and mortality in postmenopausal women. *JAMA* 1997;277:1287–92.
33. Bijnen F, Feskens E, Caspersen C, et al. Baseline and previous physical activity in relation to mortality in elderly men. *American Journal of Epidemiology* 1999;143:54–62.
34. Glass T, Leon C, Marottoli R, et al. Populations based study of social and productive activities as predictors among elderly Americans. *BMJ* 1999;319:478–83.
35. Swank AM, Condra S, Yates JW. Effect of long-term tennis participation on aerobic capacity, body composition, muscular strength and flexibility and serum lipids. *Sports Med Training Rehab* 1998;8:99–112.
36. Mensink G, Ziese T, Kok F. Benefits of leisure-time physical activity on the cardiovascular risk profile at older age. I*nternational Journal of Epidemiology* 1999;28:659–66.
37. Reaven P, Barrett-Connor E, Edelstein S. Relation between leisure-time physical activity and blood pressure in older women. *Circulation* 1991;83:559–65.
38. Agrotou S, Karatzi K, Papamichael C, et al. Effects of chronic anaerobic training on markers of sub-clinical atherosclerosis. *Hellenic J Cardiol* 2013;54:178–85.
39. Lawrence RD. The effect of exercise on insulin action in diabetes. *Br Med J* 1926;1(3406):648–50.
40. Nessler A. Sportmedizinische Befunde und sportpraktische Erfahrungen zum Tennis unterricht in der Bewegungstherapie von Typ-2-Diabetikern. Thesis. *Deutsche Sporthochschule* 2001.
41. Vodak PA, Savin WM, Haskell WL, et al. Physiological profile of middle-aged male and female tennis players. *Med Sci Sports Exerc* 1980;12:159–63.
42. Rubins HB, Robins SJ, Collins D, et al. Gemifibrozil for the secondary prevention of coronary heart disease in men with low levels of high density lipoprotein cholesterol. Veterans Affairs High-Density Lipoprotein Cholesterol Intervention Trial Study Group. *N Engl J Med* 1999;341:410–18.
43. Skoumas J, Pitsavos C, Panagiotakos D, et al. Physical activity, high density lipoprotein cholesterol and other lipid levels, in men and women from the ATTICA study. *Lipids in Health and Disease* 2003;2:3.
44. Wareham NJ, van Sluijs EM, Ekelund U. Physical activity and obesity prevention: a review of the current evidence. *Proc Nutr Soc* 2005;64:229–47.
45. Marks BL, Galleher EW, Moore T, et al. Energy balance monitoring in tennis players. *Med Sci Tennis J* 2003;8:8–9.
46. Seliger V, Ejem M, Pauer M, et alnergy metabolism in tennis. Int. Z. angew. *Physiol*. 1973;31:333–40.
47. Ferrauti A, Bergeron MF, Pluim B, et al. Physiological responses in tennis and running with similar oxygen uptake. *Eur J Appl Physiol* 2001;85:27–33.
48. Lee I, Paffenbarger R. Change in body weight and longevity. *JAMA* 1992;268:2045–49.
49. Sui X, LaMonte M, Laditka J, et al. Cardiorespiratory fitness and adiposity as mortality predictors in older adults. *JAMA* 2007;298(21):2507–16.
50. Swank AM, Condra S, Yates JW. Effect of long term tennis participation on aerobic capacity, body composition, muscular strength and flexibility and serum lipids. *Sports Med Training Rehab* 1998;8:99–112.
51. Schnieder D, Greenberg MR. Choice of exercise: a predictor of behavioral risks? *Res Q Exerc Sport* 1992;63:231–7.
52. Laforest S, St. Pierre DM, Cyr J, et al. Effects of age and regular exercise on muscle strength and endurance. *Eur J Appl Physiol Occup Physiol 1990;60(2):104–11.*
53. Ireland A, Maden-Wilkinson T, McPhee J, et al. Upper limb muscle-bone asymmetries and bone adaptation in elite youth tennis players. *Med Sci Sports Exerc* 2013;45(9):1749–58.
54. Sanchis-Moysi J, Dorado C, Olmedillas H, et al. Bone and lean mass inter-arm asymmetries in young male tennis players depend on training frequency. *Eur J Appl Physiol* 2010;110(1):83–90.
55. Ducher G, Bass SL, Saxon L, et al. Effects of repetitive loading on the growth-induced changes in bone mass and cortical bone geometry: a 12-month study in pre/peri- and postmenarcheal tennis players. *J Bone Miner Res* 2011;26(6):1321–9.
56. Ducher G, Daly RM, Bass SL. Effects of repetitive loading on bone mass and geometry in young male tennis players: a quantitative study using MRI. *J Bone Miner Res* 2009;24(10):1686–92.
57. Ducher G, Tournaire N, Meddahi-Pelle A, et al. Short-term and long-term site-specific effects of tennis playing on trabecular and cortical bone at the distal radius. *J Bone Miner Metab* 2006;24(6):484–90.
58. Dimov M, Khoury J, Tsang R. Bone mineral loss during pregnancy: is tennis protective? *J Phys Act Health* 2010;7(2):239–45.
59. Pluim B, Safran M. *From breakpoint to advantage: A practical guide to optimal tennis health and performance*. Vista, CA: USRSA, 2004.
60. Kohrt WM, Bloomfield SA, Little KD, et al. Physical activity and bone health. *Medicine and Science in Sports and Exercise* 2004;36(11):1985–96.
61. Middleton LE, Mitnitski A, Fallah N, et al. Changes in cognition and mortality in relation to exercise in late life. *PLoS One* 2008;3(9):e3124.

62. Hakim AA, Petrovitch H, Burchfiel CM, et al. Effects of walking on mortality among nonsmoking retired men. *N Eng J Med* 1998;338(2):94–99.
63. Kramer AF, Hahn S, Cohen NJ, et al. Ageing, fitness and neurocognitive function. *Nature* 1999;400:418–19.
64. Kramer AF, Erickson KI, Colcombe SJ. Exercise, cognition, and the aging brain. *Journal of Applied Physiology* 2006;101(4):1237–42.
65. Colcombe SJ, Erickson KI, Raz N, et al. Aerobic fitness reduces brain tissue loss in aging humans. *J Gerontol A Biol Sci Med Sci* 2003;58(2):176–80.
66. Rogers RI, Meyer JS, Mortel KF. After reaching retirement age physical activity sustains cerebral perfusion and cognition. *J Am Geriatr Soc* 1990;38(2):123-28.
67. Chan JS, Yan JH, Pavne VG. The impact of obesity and exercise on cognitive aging. *Front Aging Neurosci* 2013;20(5):97.
68. Black JE, Isaacs KR, Anderson BJ, et al. Learning causes synaptogenesis, whereas motor activity causes angiogenesis in cerebellar cortex of adult rats. *Proceedings of the National Academy of Sciences (USA)* 1990;87:5568–72.
69. Pereira AC, Huddleston DE, Brickman AM, et al. An in vivo correlate of exercise-induced neurogenesis in the adult dentate gyrus. *Proceedings of the National Academy of Sciences (USA)* 2007;104(13):5638–43.
70. Reuben DB, Judd-Hamilton L, Harris TB, et al. The association between physical activity and inflammatory markers in high-functioning older persons. *J Am Geriatr Soc* 2003;51(8):1125–30.
71. Bloomstrand E, Perrett D, Parry-Billings M, et al. Effects of sustained exercise on plasma amino acid concentrations and on 5 hydroxytryptamine metabolism in six different brain regions in the rat. *Acta Physiol Scand* 1989;136(3):473–81.
72. Borst SE, Vincent KR, Lowenthal DT, et al. Effects of resistance training on insulin-like growth factor and its binding proteins in men and women aged 60 to 85. *J Am Geriatr Soc* 2002;50(5):884–88.
73. Spirduso WW, Clifford P. Replication of age and physical activity effects on reaction time movement time. *Journal of Gerontology* 1978;33:23–30.
74. Etnier JR, Salazar W, Landers DM, et al. The influence of physical fitness and exercise upon cognitive functioning: A meta-analysis. *Journal of Sport and Exercise Psychology* 1997;19:249–77.
75. Hillman CH, Erickson KI, Kramer AF. Be smart, exercise your heart: exercise effects on brain and cognition. *Nat Rev Neurosci* 2008;9:58–65.
76. Sibley BA, Etnier JR. The relationship between physical activity and cognition in children: A meta-analysis. *Pediatr Exerc Sci* 2003;15:243–56.
77. Angevaren M, Aufidemkampe G, Verhaar HJ, et al. Physical activity and enhanced fitness to improve cognitive function in older people without known cognitive impairment. *Cochrane Database Syst Rev* 2008;3(CD005381).
78. Colcombe S, Kramer AF. Fitness Effects on the Cognitive Function of Older Adults: A Meta-Analytic Study. P*sychological Science* 2003;14(2):125–30.
79. Cotman CW, Berchtold NC, Christie LA. Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychol Sci* 2007;14:125–30.
80. Smith PJ, Blumenthal JA, Hoffman BM, et al. Aerobic exercise and neurocognitive performance: a meta-analytic review of randomized controlled trials. *Psychosom Med* 2010;72:239–52.
81. Iacoboni M. Playing tennis with the cerebellum. Nat Neurosci 2001;4:555–6
82. Kerr JH, Fauiyama H, Campano J. Emotion and stress in serious and hedonistic leisure sport activities. *J Leisure Res* 2002;34:272–89.
83. Spiriduso W, Clifford P. Replication of age and physical activity effects on reaction and movement time. *J Gerontol* 1978;33:26–30.
84. Rotella RJ, Bunker KL. Field dependence and reaction time in senior tennis players (65 and over). *Percept Motor Skills* 1978;46:585–86.
85. Wang CH, Chang CC, Liang YM, et al. Temporal preparation in athletes: a comparison of tennis players and swimmers with sedentary controls. *J Motor Behav* 2013;45(1):55–63.
86. Overney LS, Blanke O, Herzog MH. Enhanced temporal but not attentional processing in expert tennis players. *PLoS One* 2008;3(6):e2380.
87. Hamer M, Stamatakis E, Steptoe A. Dose-response relationship between physical activity and mental health: the Scottish Health Survey. *British Journal of Sports Medicine* 2009;43:1111–14.
88. Romero Carrasco AE, Zapata C, Letelier Lopez A, et al. Autonomy, coping strategies and psychological well-being in young professional tennis players. *The Spanish Journal of Psychology* 2013;16:E75.
89. Stubbe JH, de Moor MH, Boomsma DI, et al. The association between exercise participation and well-being: a co-twin study. *Prev Med* 2007;44:148–52.
90. Casper JM, Gray DP, Stellino MB. A sport commitment model perspective on adult tennis players' participation frequency and purchase intention. *Sport Management Review* 2007;10(3):253–78.
91. Bloomfield J, Blanksby BA, Ackland TR, et al. The anatomical and physiological characteristics of preadolescent swimmers, tennis players and noncompetitors. *Australian Journal of Science and Medicine in Sport* 1985;17(3):19–23.
92. Bloomfield J, Blanksby BA, Beard DF, et al. Biological characteristics of young swimmers, tennis players, and non-competitors. *Br J Sports Med* 1984;8:97–103.
93. Mero A, Jaakkola L, Komi PV. Neuromuscular, metabolic and hormonal profiles of young tennis players and untrained boys. *Journal of Sports Sciences* 1989;7:95–100.
94. Keul J, Stockhausen W, Pakan R, et al. Metabolische und kardiozirkulatorische adaptation sowie leistungsverhalten professioneller tennisspieler Metabolic and cardiovascular adaptation and performance of professional tennis players. *Deutsche Medizinische Wochenschrift* 1991;116:761–7.
95. Angevaren M, Vanhees L, Wendel-Vos W, et al. Intensity, but not duration, of physical activities is related to cognitive function. *Eur J Cardiovasc Prev Rehabil* 2007;14:825–30.