Anthocyanin-rich blackcurrant supplementation as a nutraceutical ergogenic aid for exercise performance and recovery: A narrative review

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Abbreviations: IL-6, interleukin-6; LIST, Loughborough intermittent shuttle test; Nrf2-Keap1, Kelch-like ECH-associated protein 1-nuclear factor erythroid 2-related factor 2; NZBC, New Zealand blackcurrant; TNFα, tumor necrosis factor alpha $\dot{V}O_{2max}$, maximum oxygen uptake.

Abstract

Athletes and physically active individuals consume sports nutrition supplements to enhance competitive sport performance and exercise recovery. Polyphenols have emerged as a promising area of research with application for sport and exercise nutrition due to affecting physiological mechanisms for exercise performance and recovery. The anthocyanin is a polyphenol that can be abundantly present in dark-colored fruits, berries and vegetables. Anthocyanins and anthocyanin-induced metabolites will provide antioxidant and anti-inflammatory effects. The focus in this narrative review is on the observations with intake of anthocyanin-rich blackcurrant supplements on *whole-body* exercise performance and exercise recovery. This review included a total number of 17 studies with a randomized placebo-controlled cross-over design (10 studies on performance and 8 on recovery effects) and 1 with a randomized placebo-controlled parallel group design (recovery effects). Among the performance studies, 6 studies (60%) reported positive effects, 3 studies (30%) reported no significant effects and 1 study (10%) reported a mixed outcome. Among the recovery studies, 7 studies (78%) reported positive effects, 1 study (11%) reported no significant effects and 1 study (11%) reported a negative effect. Studies with intake of supplements made from New Zealand blackcurrants (dose: 1.8 to 3.2 $mg \cdot kg^{-1}$ and 105 to 315 mg of anthocyanins, acute to 7-day intake) have provided meaningful (but not always consistent) effects on continuous and intermittent exercise performance tasks (i.e. rowing, cycling and running) and markers for exercise recovery. A mechanistic understanding for the beneficial exercise effects of anthocyanins for athletes and physically active individuals is still limited. Future work requires a better understanding of the specific types of anthocyanins and anthocyanin-induced metabolites and their effects on altering cell function that can enhance exercise performance and recovery.

Keywords: blackcurrant; anthocyanins; sports nutrition; exercise performance; exercise recovery

Summary

Studies with New Zealand blackcurrant extract have provided meaningful effects for exercise with different duration and intensities and exercise recovery.

Introduction

Tissues of higher plants contain the flavonoid compound anthocyanins (1). Anthocyanins are anthocyanidins aglycones with incorporation of one or more carbohydrates. The diversity in chemical structures of the anthocyanidins aglycones allowed the identification of hundreds of anthocyanins (2). In higher plants, the anthocyanins contribute to the color variety of berries and fruits (2), and offer protection against environmental stresses (3). For humans, the presence of the anthocyanins in the leaves, the seeds, the berries and the fruits make them readily available for consumption. Humans consume primarily the anthocyanidins cyanidin, delphinidin, malvidin, pelargonidin, peonidin and petunidin (4). In Europe, for example, intake of total anthocyanidins for men and women were 64.88 (SE 1.86) and 44.08 (SE 2.45) mg·day^{-1} (4). The evidence for the health-related effects of anthocyanin intake is growing, where benefits have been shown to include a reduced risk for cardiovascular disease and type 2 diabetes [for reviews see e.g. (5, 6, 7)]. However, no dietary guidelines exist yet for the amount of intake of anthocyanins as part of a healthy diet. In fact, among the thousands of flavonoids, an intake recommendation of 400-600 mg·day^{-1} only exists for flavan-3-ols, due to reported cardio-metabolic health implications (8). Existing and future research on the effects of the intake of anthocyanins in humans [with focus on beneficial health effects [e.g. (9)] will eventually provide the evidence to support intake recommendations for anthocyanins.

For the blackcurrant, of the 15 anthocyanins present, cyanidin-3-*O*-glucoside, cyanidin-3-*O*-rutinoside, delphinidin-3-*O*-glucoside and delphinidin-3-*O*-rutinoside make up more than 97% of the total anthocyanin content (10). However, different fruits and berries have their own unique anthocyanin composition (11). For anthocyanins, the low plasma bioavailability [e.g. (12)] strongly indicates that the numerous anthocyanin-induced metabolites are causally linked with providing the health effects (13). The health-related effects of anthocyanin intake are thought to be due to providing antioxidant, anti-inflammatory and immunomodulatory effects (14, 15). In support, the intake of anthocyanins (~35 mg of chokeberry anthocyanins daily for 4 weeks) can enhance the endogenous antioxidant system (16). However, note that the antioxidant capacity of the individual anthocyanins contributes to the total antioxidant capacity relative to the weight of the berry (11). The potential of plant compounds to enhance the antioxidant capacity of human tissues as well as inhibition of the exercise-induced inflammatory response suggest the ergogenic potential for applications in sport and exercise. Such application has been shown, for example, for some of the flavan-3-ols in green tea extract with the ability to affect fat metabolism [for a review see (17)]. The ability of skeletal muscle tissue to enhance cellular antioxidant defense may limit exercise-induced fatigue (18), and enhance exercise performance (19). However, it was only in the study by Matsumoto et al (12) in which first observations were provided of fatigue-lowering responses in humans in a non-exercise study after intake of blackcurrant anthocyanins. Following an acute intake of 17 mg·kg body weight^{-1} of blackcurrant anthocyanins, there was an increase in left forearm blood flow using near infrared spectroscopy during typing activity and changes in maximum total hemoglobin in the trapezius after maximal voluntary contractions after the typing (12). In addition, an intake for 2 weeks of 7.7 mg·kg body weight^{-1} tended to lower the muscle activity (i.e. lower EMG root mean square) during intermittent typing work, suggestive of a reduction in muscle fatigue (12). The observations by Matsumoto et al (12) seemed not to have been recognized for some years and only in the last decade, many studies have addressed the efficacy of blackcurrant anthocyanin intake on the physiological, cardiovascular and metabolic responses during exercise as well as the potential to affect exercise recovery.

In this narrative review, the focus will be on the studies that provided experimental evidence for the efficacy of anthocyanin-rich blackcurrant supplements (not whole food) to enhance *whole-body* exercise performance and recovery. Studies on effects in muscle groups will not be considered [e.g. (20, 21)]. Studies with combined intake of supplements including anthocyanin-rich blackcurrant and conference proceedings will not be considered. For the purpose of this review, exercise performance is considered a task completion that may provide competitive advantage, e.g. a faster running sprint time, cycling time-to-exhaustion or cycling time-trial. Recovery is considered the observable physiological, metabolic and functional phenomena after completion of an exercise task, so not solely an exercise performance task during the recovery phase. Animal and *in-vitro* studies will only be considered for the purpose of our understanding of the potential causal mechanism by the intake of anthocyanins for the exercise performance and exercise recovery effects in humans. We will consider the strengths and the limitations of the experimental studies in humans and highlight the substantial gaps that still exist in our understanding of the optimal dosing strategy and the mechanisms for *whole-body* exercise performance and recovery effects by intake of anthocyanin-rich blackcurrant. As the first studies on the effects of anthocyanin intake examined post-exercise effects, the review will cover first the studies on recovery and subsequently the studies on the exercise performance effects. Observations from studies with clinical cohorts will only be covered when they allow insight into the mechanism for the exercise and recovery effects. It is not within the scope of this narrative review to provide detailed commentary on the metabolism of anthocyanin-induced metabolites and *whole-body* physiological mechanisms underpinning the performance enhancing and exercise recovery effects. With the information available, the literature has provided meaningful observations with primarily intake of anthocyanin-rich supplementation made from New Zealand grown blackcurrant. New Zealand grown blackcurrant has higher levels of anthocyanins compared to non-New Zealand grown blackcurrant (22). The available evidence obtained with studies on the effects of anthocyanin-rich blackcurrant will justify future work on the intake of a variety of anthocyanin-rich natural supplements to advance the field of sport and exercise nutrition (23, 24).

Early evidence on the effect of intake of anthocyanins on exercise recovery in humans

The required time for the functional and physiological recovery from exercise-induced effects, e.g. structural muscle damage, muscle soreness, muscle dysfunction, oxidative stress and inflammation, can take days to weeks. The occurrence of these exercise-induced effects will depend largely on the intensity and duration of the exercise, particularly when the exercise was of an unaccustomed nature (25, 26). In a physical exercise training program, the exercise-induced oxidative stress and the inflammatory response post-exercise contribute to the physiological adaptation processes [e.g. (27) and for a review see (28)]. In addition, adaptations from physical training can include an enhanced endogenous antioxidant system (29). Therefore, regular intake of polyphenols (including anthocyanins) in the diet is a non-exercise nutritional means for enhancing the endogenous antioxidant system (30). An enhanced endogenous antioxidant system is beneficial for coping with exercise-induced oxidative stress. One of the first studies to examine the effects of chronic intake of anthocyanins on exercise-induced oxidative stress was with chokeberry juice (16). Chokeberry juice is composed of up to 98.7% of cyanidin glycosides and consist of cyanidin-3-*O*-galactoside, cyanidin-3-*O*-glucoside, cyanidin-3-*O*-arabinoside and cyanidin-3-*O*-xyloside (31). Pilaczynska-Szczesniak et al (16) dosed 19 male elite rowers (members of the Polish rowing team) with chokeberry (*Aronia Melanocarpa L.*) juice (3 x 50 mL per day) for 4 weeks. The chokeberry juice in the study contained 23 mg of anthocyanins per 100 mL. Four weeks intake of the chokeberry juice reduced levels of thiobarbituric acid reactive substances, a measure of lipid peroxidation, 1 minute and 24 hours post-exercise following an incremental rowing protocol, providing support for enhancement of the antioxidant defense system and therefore enhanced recovery (16). The enhanced endogenous antioxidant system by polyphenol intake or exercise is due to the Kelch-like ECH-associated protein 1-nuclear factor erythroid 2-related factor 2 (Nrf2-Keap1) system (32, 33). Evidence for the activation of the Nrf2-Keap1 system by chokeberry, however, remains absent from the literature, but is present for example for raspberry (primarily containing cyandin-3-*O*-glucoside) in human HepG2 cells (34). It is surprising that considering the dark-blue colored chokeberry to be a very rich source of polyphenols with anthocyanins (35), no studies with chokeberry intake in humans have provided exercise performance-enhancing effects (36). It is possible that some anthocyanin-rich berries may provide beneficial effects for exercise recovery without a performance-enhancing effect. One of the key messages of the present review is, therefore, that future work needs to address the specificity of the anthocyanins or combination of anthocyanins that can be effective for both exercise recovery and performance or those single or combination of anthocyanins that only seem to have either recovery or performance effects. Studies with such aims have not been considered or started in humans. In the C57BL/6 mouse model of polygenic obesity, for example, diets that were supplemented with different berries provided different metabolic effects, e.g. differences in both mitochondrial respiration and the dissipation of the mitochondrial proton gradient in adipose tissue (37), and fasting glucose (38). Studies in humans on the effects of single anthocyanins on physiological, metabolic, cardiovascular and exercise performance responses are absent. In addition, many reviews on the effects of polyphenols in humans have not clearly recognized the importance of the potential differences in effects by intake of different combinations of anthocyanins [e.g. (39, 40)]. In the following section, we will consider the evidence for the intake of anthocyanin-rich blackcurrant for exercise recovery.

Anthocyanin-rich Blackcurrant and Exercise Recovery

The recovery from the occurrence of exercise-induced muscle fatigue and potential muscle injury of habitual exercise training sessions will require normally not more than a few days. Athletes in preparation for competitive endurance events (e.g. marathon running) will have adopted tapering strategies to optimize recovery from the progression in training volume. However, during physical preparatory training or busy competitive schedules, an enhanced exercise recovery would benefit the athletes for undertaking subsequent exercise training sessions and competition. Studies with bioactive nutritional compounds that have antioxidant and anti-inflammatory properties provided experimental evidence to accelerate the recovery from exercise-induced muscle fatigue and muscle injury. Early studies focused on effects of antioxidant delivering ability of vitamins E and C [for a review see Evans et al (41)]. More recently, strong and abundant experimental support has emerged for the effectiveness of anthocyanin-containing tart cherry supplementation on exercise recovery providing anti-inflammatory effects. Tart cherry contains primarily the anthocyanins cyanidin-3-glucosylrutinoside and cyanidin-3-rutinoside, i.e. ~ 42% and 35% of total anthocyanins [e.g. (42)]. In a systematic review and meta-analysis on tart cherry supplementation (43), small beneficial effects were reported after strenuous exercise for muscle soreness (effect size: -0.44), sprint time (effect size: -0.32), C-reactive protein (effect size: -0.46) and interleukin-6 (effect size: -0.35), moderate effects for muscle strength (effect size: -0.78) and muscular power (effect size: -0.53) and large effects for jump height (effect size: -0.82).

In studies on the effects of intake of blackcurrant on exercise recovery, meaningful effects have been reported for the recovery from different exercise modalities that had variation for exercise duration and intensity (**Table 1**). As far as we know, the first study to examine the exercise recovery effects with intake of blackcurrant was done by the New Zealand Institute for Plant and Food Research Ltd (44). Lyall et al (44) examined the exercise recovery effects by the intake of

120 mg of blackcurrant anthocyanins before and after 30 min of indoor rowing at 80% $\dot{V}O_{2max}$ in a recreationally active cohort (5 females, 5 males) with a broad age range (37 to 63 yrs, mean±SD: 48±3 yrs). Blackcurrant lowered protein carbonyl levels 30-min after exercise that were normally elevated by ~40% by the indoor rowing at 80% $\dot{V}O_{2max}$ and indicative of oxidative stress. The effect was of short duration as blackcurrant had no effect on plasma protein carbonyl levels at 1, 2 and 24 hr during recovery, but observations on IL-6, TNFα and creatine kinase were indicative of lower inflammation and reduced muscle damage. In the study by Lyall et al (44), the dosing strategy was not justified. However, based on the dosing information, intake of 120 mg of blackcurrant extract was effective within 30 min, suggesting not only fast bioavailability of anthocyanins and anthocyanin-induced metabolites [e.g. Costello et al (45) for presence over 6 hr and Czank et al (46) for 48 hr] but maybe also rapid physiological antioxidative stress effects. However, the potential effects of the many metabolites, e.g. protocatechuic acid, vanillic acid and gallic acid (45, 46), on the alteration of *in-vivo* cell function are not known. In addition, Czank et al (46) identified 24 metabolites and observed substantial interindividual differences in recovery rate (15.1% to 99.3%) of a total of 25 ^{13}C-labeled compounds that consisted of $^{13}C_5$-cyanidin-3-glucoside and the 24 labeled metabolites. The distribution, metabolism and excretion of the anthocyanin-induced metabolites is beyond the focus of this narrative review. As far as we know, no information is available on the plasma availability of anthocyanins and parent metabolites by different intake strategies of blackcurrant over a long period of time [see Kalt et al (47) for a study with intake of blueberry juice]. In addition, more understanding is needed for the role of the gut microbiome on the plasma availability of anthocyanins and parent metabolites [for reviews see (48, 49)]. In a subsequent study by the New Zealand Institute for Plant and Food Research Ltd, 30 min of indoor rowing at 70% $\dot{V}O_{2max}$ in healthy individuals reduced plasma protein carbonyl levels

not at 0 hr but 2 hr during recovery (compared to 0 hr) with 0.8 and 1.6 $mg \cdot kg^{-1}$ blackcurrant (50). Thus, studies show inconsistent observations on plasma protein carbonyl levels as a marker of oxidative stress after exercise with intake of blackcurrant (44, 50). Another marker of oxidative stress, i.e. the lipid oxidation product malondialdehyde was reduced 2 hr after 30 min of indoor rowing at 70% $\dot{V}O_{2max}$ in healthy individuals with similar efficacy with acute (1 hr before) and 5 weeks daily intake of 3.2 $mg \cdot kg^{-1}$ (~ 240 mg) of blackcurrant anthocyanins (51). In addition to the evidence of enhanced recovery with markers of oxidative stress, Lyall et al (44) also observed blunting of the rise in creatine kinase levels 24 hr after exercise, an indication that blackcurrant affects the symptoms of exercise-induced muscle damage. This was observed in a study by Hunt et al (52) in which 12 days of daily intake of 105 mg of blackcurrant anthocyanins in extract form (8 days prior and 4 days following exercise) reduced muscle soreness and creatine kinase levels during the recovery from 4x15 maximal concentric and eccentric contractions of the biceps brachii muscle. However, no enhanced functional recovery was shown in Hunt et al (52). In contract, muscle soreness and countermovement jump variables were not affected by intake of blackcurrant anthocyanins (7-days prior and 2 days after with 210 mg anthocyanins per day) following a half-marathon run in recreationally runners (n=20, 8 females) (53). In addition, no effect on muscle soreness was reported after eccentric squatting in healthy participants (n=24, 6 females) with intake of blackcurrant nectar (2x per day for 8 days with ~ 370 mg anthocyanins per day) but with lower creatine kinase responses (54). In Perkins et al (55), the absolute lactate levels declined faster during recovery from an intermittent high-intensity running protocol in recreationally active male team sport players following a 7-day intake of 105 mg of blackcurrant anthocyanins in extract form. Faster decline for absolute lactate levels during recovery was also shown in the 20-min after completion of a 16.1 km time trial (56). However, the recovery phase in the blackcurrant conditions in Perkins et al (55) and Cook et al (56) were initiated with higher lactate levels suggesting a potential role for the mass action effect. In a cycling study by Murphy et al (57), the time to complete a 4 km time trial following 10-min of active recovery after a 4 km time trial was not enhanced. With the information available, studies on effects of New Zealand blackcurrant extract have not provided convincing evidence for enhanced endurance performance during a short exercise recovery period. In addition, it remains unclear whether the potential enhanced exercise recovery by intake of New Zealand blackcurrant is beneficial for non-endurance exercise tasks. Athletes will only benefit from enhanced exercise recovery when it would enhance subsequent competitive sport performance or allowing enhanced adaptation from subsequent physical training sessions. In the next section, we will focus on the effects of intake of blackcurrant on *whole-body* exercise performance, i.e. continuous endurance exercise and intermittent exercise.

Anthocyanin-rich Blackcurrant and Exercise Performance

Exercise performance is dependent upon multiple intrinsic (e.g. physiological and morphological components) and extrinsic factors (e.g. motivation, sleep and nutritional practices) [for a comprehensive review see (58)]. Competitive athletes are keen consumers of performance-enhancing nutritional ergogenic aids (59). The performance enhancing effects by the traditional supplements caffeine, creatine, β-alanine, sodium bicarbonate, dietary nitrate and glycerol are recognized (60), with the enhancing effects related to the intensity and duration of the exercise modality [e.g. for a review on caffeine (61)]. Anthocyanins have emerged as a performance-enhancing nutritional aid (24). This may be linked with the known potency to scavenge active oxygen species, with first *in-vivo* evidence in the liver of rats (62). At that time, there was also the concern for a role for reactive oxygen species affecting mechanisms to provide higher peripheral muscle fatigue (63). However, it needs to be noted that there is no convincing evidence for an antioxidant *free radical* scavenging effect by intake of anthocyanins in *in-vivo* contracting human skeletal muscle. Nevertheless, postponing in a meaningful way the peripheral (and central) fatigue mechanisms by physical training modalities or different traditional and non-traditional nutritional supplements (e.g. blackcurrant supplementation) has the potential to enhance exercise performance.

Whole-body continuous endurance exercise

Many studies, primarily from the University of Chichester (United Kingdom), have shown enhanced exercise performance effects for a variety of exercise tasks but with some inconsistency in the findings (**Table 2**). In Cook et al (56), first observations were provided for the effectiveness of New Zealand blackcurrant extract (7x105 mg anthocyanins$\cdot$day^{-1}) on a 16.1 km ergometer cycling time trial in trained male cyclists (n=14, $\dot{V}O_{2max}$: 53±6 mL$\cdot$kg$^{-1}\cdot$min^{-1}). To be included in the study, participants had to cycle 8-10 hours a week in addition to having a personal best time for a 16.1 km under 30 min. The non-paid cohort of trained male cyclists in Cook et al (56) had two full familiarizations as part of the study. Full familiarization is a methodological necessity that is required to minimize or exclude task learning effects and even more essential for participants unfamiliar with an exercise task (64). More than one full familiarization may be essential to avoid the variation in the performance of unfamiliar tasks even for a trained cohort. In Cook et al (56), eleven participants had an increase in 16.1 km cycling time trial performance with a cohort observation of an increase in time of 2.4% (placebo: 1722±131 s, New Zealand blackcurrant extract: 1678±108 s). The enhanced performance time of 2.4% was similar to what has been observed with acute intake of beetroot juice (0.5 L with 6.2 mmol of nitrate) for a cycling time trail of 16.1 km (i.e. 2.7% increase) in competitive male cyclists (n=9, $\dot{V}O_{2max}$: 56.0±5.7 mL·kg^{-1}·min^{-1}) (65). The study by Lansley et al (65) also had two full familiarizations. A higher enhanced 15 km cycling performance time of 4.6% was observed with 6 days intake of Montmorency cherry powder (257 mg·day^{-1} of anthocyanins) in trained male cyclists (n=8 and two full familiarizations) (66). The early work with 7-day dosing with New Zealand blackcurrant extract raised the question whether there may be an effect by the last dose on the day of testing. Recent work on the dosing time before exercise with Montmorency cherry indicated that ~90 min before was better for enhanced 15 km cycling time trial performance than ~30 min and ~150 min before (67). In Montanari et al (68), an acute intake of 315 mg of anthocyanins in male and female cyclists (fully familiarized two times, n=34, $\dot{V}O_{2max}$: 57±5 mL·kg^{-1}·min^{-1}, 8 females), 120 min before enhanced performance for the 16.1 km cycling time trial, but only in the slower cyclists (i.e. >1400 s during the familiarizations). It is possible that the 80% positive response rate to intake of blackcurrant in Cook et al (56) was related to the cohort being considered slow cyclists according to Montanari et al (68). It needs to be noted also that the study by Montanari et al (68) was a home-based study during Covid lockdown in which participants were informed that the acute 16.1 km cycling performance effects of two different products were tested. This approach is uncommon in sports nutrition research in which a randomized, placebo-controlled, cross-over design remains the gold standard. Nevertheless, in Montanari et al (68) was evidence that for some athletes, beneficial cycling performance-enhancing effects can be obtained with acute intake of New Zealand blackcurrant extract. Interestingly, a role for aerobic fitness level was also shown for nitrate loading with lower increases in plasma nitrate in those with high $\dot{V}O_{2peak}$ and less improvement in 3-km field running time trial (69). Therefore, we cannot exclude that anthocyanin-induced metabolite availability by intake of New Zealand blackcurrant contributes to interindividual responses (and potentially non-responses) in enhancement of exercise performance.

In trained male runners (n=16, $\dot{V}O_{2max}$: 55±6 mL·kg^{-1}·min^{-1}), an acute intake of 315 mg anthocyanin-rich New Zealand blackcurrant extract enhanced 5 km treadmill running performance by 2.8% (placebo time: 1346.33 ± 124.44 s) with 88% of the participants responding (70). Future work is required to examine whether higher acute dosing is required to enhance the overall response rate in performance studies. In addition, it is not known whether prolonged dosing is required for the faster cyclists (<1400 s for a 16.1 km cycling time trial) in the study by Montanari et al (68), and whether a dosing strategy for anthocyanin-rich New Zealand blackcurrant can exist that provides a 100% meaningful response for performance enhancement in all participants. For caffeine, for example, a role for genetics is apparent for the interindividual response on cycling time trial performance [for a meta-analysis see Wang et al (71)]. For the ability of anthocyanins to enhance exercise performance, there is no research on the potential role of genetics to explain interindividual differences by intake of blackcurrant anthocyanins [see for example Miranda-Vilela et al (72) for effects of gene polymorphisms on response to intake of pequi-oil supplementation]. Interestingly, a study on the effects of pomegranate in patients with biochemical recurrence following treatment for prostate cancer showed ability to respond in those with the manganese superoxide dismutase (a mitochondrial antioxidant enzyme) genotype (73). However, non-genotype factors will also contribute to variability of responses. For example, in a study on the dose (105 and 210 mg of blackcurrant anthocyanins) and time (acute, 4 and 7 days) response to intake of New Zealand blackcurrant extract the response for performance enhancing effects for the 16.1 km cycling time trial was inconsistent (74). For this study, eleven visits were required including washout periods of at least two weeks resulting in completion times from 3 to 11 months

(74). It is possible that the time period to complete all testing allowed unwanted variation due to changes in seasonal activity lifestyles of the participants. In addition, the study had consistent morning testing for only 3 of the 13 participants (74). In a study by Boyett et al (75), trained male cyclists (n=7) responded with a higher performance effect during morning testing for a 3-km cycling time trial compared to evening testing with intake of caffeine (6 mg · kg body weight^{-1}). Future studies should address whether the time of day can affect the performance-enhancing potential of anthocyanin-rich New Zealand blackcurrant for trained athletes. In addition, the observations on potential time-of-day effects would also inform our knowledge on the optimal dosing strategy required for time-of-day competitive athletic events. In another running study, Pastellidou et al (76) examined the effect of New Zealand blackcurrant extract (315 mg of anthocyanins with 1-day preloading) on time-to-exhaustion running test at two different intensities in recreationally active males (n=15, $\dot{V}O_{2max}$: 53.1±3.4 mL·kg^{-1}·min^{-1}). Time-to-exhaustion exercise performance tests compared to time-trials are known to have high variation (i.e. > 10%) (77). Nevertheless, two time-to-exhaustion tests, one at critical speed (finish time: 1540–2284 s) and one at 110% of $\dot{V}O_{2max}$ (185-367 s) provided no cohort effects, but the authors suggested a performance enhancing effect for 60% the participants by 10-20% (76). Only one study examined the endurance performance enhancing potential of intake of 7 days of New Zealand blackcurrant extract (210 mg per day) in a *stressful* environmental condition (normobaric hypoxia: ~15% of oxygen, i.e. ~2500 m) and found no effect in trained male cyclists (n=11, age: 38±11 y, $\dot{V}O_{2max}$: 47±5 mL·kg^{-1}·min^{-1}) for a 16.1 km time trial (78). In addition, in trained male cyclists (n=10), there was not convincing evidence for a performance-enhancing effect (7 days intake of 105 mg anthocyanins per day) for a 4 km time trial (57). It is possible that the study was underpowered.

However, when a second 4 km time trail was performed, the total time for the two 4 km time trails was 0.82% faster (57).

There is an absence of exercise performance studies with female cohorts with intake of anthocyanin-rich blackcurrant [see Smith et al (60) for a call for inclusion of females in sports nutrition studies]. In the only study with performance testing of an outdoor 5-km run in trained female runners (n=23, age: 31±8 years, $\dot{V}O_{2max}$: 49±4 $mL \cdot kg^{-1} \cdot min^{-1}$), the intake daily over three weeks in a training block was a fruit drink concentrate (of unknown composition) mixed with blackcurrant extract providing 300 mg of anthocyanins and 15 mg vitamin C (79).

In summary, there is limited and not always consistent evidence for an endurance performance enhancing effect of intake of New Zealand blackcurrant. The available observations seem to indicate that there is no effectiveness for performance enhancement for relatively short continuous best effort endurance tasks. More work is needed on the required dosing strategies (dose and time) with New Zealand blackcurrant for enhancing endurance performance in specific female and male cohorts with different athletic endurance abilities (e.g. 5 km and half-marathon runners) and various endurance exercise modalities (e.g. rowing and cross-country skiing). In addition, future work is recommended to examine performance enhancement by intake of New Zealand blackcurrant in combination with metabolomic approaches (80), that may support the understanding of interindividual responses.

Whole-body intermittent exercise

Many team sports require repeated high-intensity and maximal-intensity bouts of exercise, e.g. jumping in volleyball and repeated running sprints in football, field hockey and rugby sevens [e.g. (81, 82). The exercise-induced oxidative and inflammatory stress during repeated running sprints is probably higher than the oxidative stress during continuous exercise [for a role of exercise intensity on oxidative stress, see (83)]. The first study on the effects on repeated and incremental high-intensity exercise by Perkins et al (55) showed substantial changes in treadmill running performance with 7-day intake of New Zealand blackcurrant extract (105 mg anthocyanins per day) in participants with experience in sports with high-intensity intermittent exercise (**Table 3**). In short, participants performed stages with six repeated high-intensity treadmill running bouts of 19 s each (starting speed at 80% of the running speed at $\dot{V}O_{2max}$) with an active recovery of 15 s and passive recovery of 60 s between the incremental stages to the point of voluntary exhaustion [for more details see Perkins et al (55)]. The protocol used in Perkins et al (55) was adapted from Mukherjee and Shia (84) for the testing of running capability in soccer players. For the cohort, the speed of the first running bout was 11.5±5.7 $km \cdot h^{-1}$ and the speed at exhaustion was 18.0±1.2 $km \cdot h^{-1}$ with active recovery speeds 7.2±3.6 $km \cdot h^{-1}$. With the intake of New Zealand blackcurrant extract, participants were able to have a larger number of running bouts (placebo: 32±4, blackcurrant: 35±6, P=0.02). In addition, the distance that was covered during the high-intensity treadmill running bouts was increased by 10.8% (placebo: 2572±421 m, blackcurrant: 2849±570 m, P=0.024). Such effectiveness for New Zealand blackcurrant extract for high-intensity treadmill running bouts justifies future work whether there is application in *real-world* competitive team sports settings [e.g. (85)], in addition to providing meaningful performance effects in elite athletes (86).

The effect of New Zealand blackcurrant extract (7-day of 105 mg anthocyanins per day) was also examined in the performance of the Loughborough intermittent shuttle test (LIST) (87), a test mimicking also the physical demands of football. The LIST consists of 5 x 15-min blocks with distance running at set speeds and 9 to 10 maximal 20 m sprints. It was only in the final two blocks (i.e. after 45 min of exercise) that the effectiveness of New Zealand blackcurrant extract became apparent with reduced slowing of the maximal sprint times (87). This may indicate that a level of fatigue [see Daab et al (88) for peripheral and central fatigue during the LIST] is required for meaningful effectiveness of intake of New Zealand blackcurrant to enhance exercise performance. However, on completion of the 5 x 15 min blocks, no effect was observed for a time to exhaustion running task (87). This may indicate that the effectiveness of New Zealand blackcurrant extract to enhance exercise performance in a fatigued state may be task-dependent. Studies by Godwin et al (89) and Potter et al (90) also seem to confirm that some level of fatigue is required for New Zealand blackcurrant to enhance exercise performance. New Zealand blackcurrant extract (7-day intake of 210 mg anthocyanins per day) became only effective after the 4th sprint in trained youth football players during the running based anaerobic sprint test. However, in the same study, New Zealand blackcurrant extract had no effect in recreationally active football players during the running based anaerobic sprint test (89). In Potter et al (90), a trend (P=0.062) for a larger hang time and enhancement of sports climbing performance was reported but potential methodological and analytical issues were raised [for a critique of the study see (91)].

As far as we know, the only cycling study with intermittent exercise was performed by Paton et al (92) in which effects of acute blackcurrant drink intake (300 mL containing 155 mg of anthocyanins, 80 mg L-theanine, 50 mg pine bark extract, 7.7 g carbohydrate) were examined in well-trained male cyclists (n=12, age: 39.5±11.4 y, $\dot{V}O_{2peak}$: 4.71±0.61 L·min^{-1}) for 8 x 5 min bouts of maximal cycling (with 2 min active recovery). No effects were observed for the blackcurrant drink (92). It is possible that a higher acute dosage or chronic dosing is required to obtain effectiveness, as was observed in Montanari et al (68), albeit for 16.1 km cycling performance in faster cyclists. Nevertheless, Paton et al (92) was the first study as well to examine acute effects by intake of an anthocyanin-rich blackcurrant drink during high-intensity intermittent exercise. Therefore, more work is required to optimize the dosing strategy for acute intake of blackcurrant anthocyanins to affect intermittent exercise performance.

Conclusions and Future Directions

Intake of anthocyanins in the studies with extracts and powder made from New Zealand blackcurrant have provided meaningful effects for whole-body exercise performance for continuous and intermittent exercise models and exercise recovery. Fruit-derived polyphenols are now recognized by the Australian Sports Commission with emerging potential as a performance enhancing nutritional aid. However, the sheer diversity of berry- and fruit-derived polyphenols including the numerous anthocyanins will provide the academic community with an enormous challenge to establish optimal evidence-based dosing strategies in sports nutrition. Many anthocyanin-rich berries, and therefore many combinations of naturally existing anthocyanins, remain unexplored regarding the efficacy for recreationally active individuals and athletes. Dosing studies with manufactured single or specific multiple anthocyanins with application for athletes are likely to remain too costly to examine for effectiveness, at least in the short term. It is expected that it will take decades for the field of anthocyanin in application for sports nutrition to provide the evidence on the dose and optimal combination of specific anthocyanins to establish maximal efficacy for exercise performance and recovery. The question remains whether the blackcurrant anthocyanins cyanidin and delphinidin have established themselves as a *winning* combination with application for sports nutrition. Time will tell! Future work on the efficacy of supplements with natural combination of berry anthocyanins is warranted to establish its potential and usefulness for the contribution of natural berry and fruit sources as an ergogenic aid in sport and exercise nutrition. In addition, future work should address also the efficacy and safety of combined intake of long-term intake of anthocyanins and other recognized sports nutrition supplements.

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Data described in the manuscript is available from the published sources considered in the narrative review.

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Table 1. Summary of studies in humans examining the effects of intake of blackcurrant anthocyanins on exercise recovery. NZBC, New Zealand blackcurrant.

Source	Cohort	Design	Dosing strategy	Exercise task	Primary recovery outcomes with NZBC
Lyall et al 2009 (44)	5 females, 5 males, age: 48±2.5 years, recreationally active	double-blind, placebo-controlled, randomized, cross-over	240 mg NZBC anthocyanins (120 mg before and after exercise)	30 min of rowing at 80% $\dot{V}O_{2max}$	↓ plasma carbonyl levels (0 h post-exercise, ↓ creatine kinase (24 h post-exercise)
Hurst et al 2019 (50)	healthy individuals, n=32, age range: 20 – 60 years	double-blind, placebo-controlled, randomized, parallel	1 x 0.8, 1.6, or 3.2 mg·kg^{-1} of NZBC anthocyanins	30 min of rowing at 70% $\dot{V}O_{2max}$	lower post-exercise (0 hr) heart rate with 0.8 and 1.6 mg·kg^{-1} blackcurrant, no effect on post-exercise lactate, ↓ plasma carbonyl levels (2 h post-exercise with 0.8 and 1.6 mg·kg^{-1} blackcurrant

Hurst et al 2020 (51)	healthy individuals, n=32, age range: 20 – 60 years	double-blind, placebo-controlled, randomized, parallel	acute (1 hr before) and 5 weeks daily intake of 3.2 mg·kg^{-1} (~ 240 mg) of NZBC anthocyanins	30 min of indoor rowing at 70% $\dot{V}O_{2max}$	↓ of malondialdehyde 2 hr post exercise with acute and chronic intake
Hunt et al 2021 (52)	healthy non-resistance trained individuals, NZBC: n=14, 10 women, age: 24±2 years); placebo: n=13, 9 women, age: 23±2 years	double-blind, placebo-controlled, randomized, parallel	each day 105 mg NZBC anthocyanins in extract form for 12 days	4 × 15 repetitions of maximal concentric and eccentric contractions of the biceps brachii muscle in the dominant arm	↓ muscle soreness at 24 and 48 hrs post-exercise, ↓ creatine kinase at 96 hrs post-exercise
Costello et al 2020 (53)	healthy individuals, NZBC: n=10, 4 women, age: 30±4 years; placebo: n=10, 4 women, age: 29±7 years	double-blind, placebo-controlled, randomized, parallel	each day 210 mg NZBC anthocyanins in extract form for 9 days	outdoor half marathon race	↑ urine IL-6 at 48 hr post-exercise
Hutchison et al 2016 (54)	healthy individuals, blackcurrant: n=8, 7 women, age: 19.5±0.3	double-blind, placebo-controlled,	each day 2x ~369 mg of blackcurrant anthocyanins (country	eccentric knee extensions (3 × 10 sets at 115% of 1-	↓ creatine kinase at 48 and 96 hrs post-exercise, ↓ plasma IL-

	years; placebo: n=8, 6 women, age: 20.9±0.9 years	randomized, parallel	unknown) in drinks for 8 days	repetition maximum	6 levels at 24 hr post-exercise)
Perkins et al 2015 (55)	13 men, recreationally active, age: 25±4 years	double blind, placebo-controlled, randomized, cross-over	105 mg NZBC anthocyanins in extract form for 7 days	progressive high-intensity, intermittent treadmill running	faster decline in blood lactate for 30-min post-exercise
Cook et al 2015 (56)	14 men, cycling 8-10 hr per week, age: 38±13 years	double blind, placebo-controlled, randomized, cross-over	105 mg NZBC anthocyanins in extract form for 7 days	16.1 km cycling time trial	faster decline in blood lactate for 20-min post-exercise
Murphy et al 2017 (57)	10 men, cyclists, age: 30±12 years	double blind, placebo-controlled, randomized, cross-over	105 mg NZBC anthocyanins, in extract form for 7 days	2 x 4 km cycling time trial with 10 min in between with active recovery	no change in time for the 2nd 4 km cycling time trial

Table 2. Summary of studies in humans examining the effects of intake of blackcurrant anthocyanins on whole-body continuous exercise performance. NZBC, New Zealand blackcurrant.

Source	Cohort	Design	Intake	Exercise task	Main outcomes
Cook et al 2015 (56)	14 men, cycling 8-10 hr per week, age: 38±13 years	double blind, placebo-controlled, randomized, cross-over	105 mg NZBC anthocyanins in extract form for 7 days	16.1 km cycling time trial (laboratory testing)	2.4% faster time
Montanari et al 2023 (68)	34 cyclists (8 women), age: 38±7 years	double blind, placebo-controlled, randomized, cross-over with participants informed that 2 different blackcurrant products were tested	acute intake of 315 NZBC anthocyanins in extract form	16.1 km cycling time trial (home-based testing)	1.3% faster time in slower cyclist (>1400 seconds for 16.1 km)
Moss et al 2023 (70)	trained male runners, n=16, age: 26±5 years	double blind, placebo-controlled, randomized, cross-over	acute intake of 315 NZBC anthocyanins in extract form	5 km treadmill running	2.7% faster times
Montanari et al 2020 (74)	13 male cyclists, age: 39±10 years	double blind, placebo-controlled, randomized, cross-over with dose effects	105 mg and 210 mg NZBC anthocyanins in extract form for 7 days	16.1 km cycling time trial (laboratory testing)	inconsistent effects with 210 mg NZBC anthocyanins

			with testing on day 1, 4 and 7		
Pastellidou et al 2021 (76)	15 males, recreationally active, age: 24.4±3.6 years	double blind, placebo-controlled, randomized, cross-over	315 mg NZBC anthocyanins extract form for 2 days	treadmill running to exhaustion at 110% of $\dot{V}O_{2max}$	no cohort effect
Willems et al 2019 (78)	11 male cyclists, age: 38±11 years	double blind, placebo-controlled, randomized, cross-over	210 mg NZBC anthocyanins extract form for 7 days	16.1 km cycling time trial (laboratory testing) in normobaric hypoxia	no cohort effect

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Table 3. Summary of studies in humans examining the effects of intake of blackcurrant anthocyanins on whole-body intermittent exercise with different intensities high intensity and maximal intensity exercise performance. NZBC, New Zealand blackcurrant.

Source	Cohort	Design	Intake	Exercise task	Main outcomes
Perkins et al 2015 (55)	13 men, recreationally active, age: 25±4 years	double-blind, placebo-controlled, randomized, cross-over	105 mg NZBC anthocyanins in extract form for 7 days	progressive high-intensity, intermittent treadmill running	increase in number of high-intensity running bouts
Willems et al 2016 (87)	13 men, recreationally active, age: 22±1 years	double-blind, placebo-controlled, randomized, cross-over	105 mg NZBC anthocyanins in extract form for 7 days	Loughborough intermittent shuttle test	reduced slowing of the 20 m maximal sprint in the final 15 min block
Godwin et al 2017 (89)	football players, recreationally active: n=15, age: 20±1 years; academy (professional club): n=9, age: 17±1 years	double-blind, placebo-controlled, randomized, cross-over	210 mg NZBC anthocyanins in extract form for 7 days	running based anaerobic sprint test	reduced slowing of sprint 5 in academy players
Paton et al 2022 (92)	12 well-trained male cyclists, age: 39.5±11.4 years	double-blind, placebo-controlled, randomized, cross-over	acute blackcurrant drink intake (300 mL containing 155	8 x 5 min maximal cycling	no effect

			mg of anthocyanins, 80 mg L-theanine, 50 mg pine bark extract, 7.7 g carbohydrate)		