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Effect of Tart Cherry Concentrate on Endurance Exercise Performance: A Meta-analysis

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ABSTRACT

Objective: Tart cherry concentrate has been shown to improve muscle function, and reduce muscle damage, oxidative stress/inflammation, and muscle soreness in athletes; however, evidence for acute endurance performance benefits is scarce. The purpose of this review was to evaluate the effect of tart cherry juice on endurance exercise performance with a meta-analysis.

Method: Data sources included Medline, Embase, Web of Science, and Google Scholar. Eligibility criteria were randomized controlled trials with endurance exercise performance tests. Participants were healthy individuals. Interventions included tart cherry supplementation and placebo ingested before, and/or on the day of exercise. Ten studies were included (totaling 127 males and 20 females). Standardized mean differences (SMD) with 95% confidence intervals were calculated for each study and pooled effects were assessed.

Results: Tart cherry concentrate in juice or powdered form, ingested for 7 days to 1.5 hours before exercise performance testing significantly improved endurance exercise performance (SMD: 0.36; 95% CI: 0.07 to 0.64; \( p = 0.01 \); \( I^2 = 0\% \)) upon pooling of the ten studies.

Conclusions: Tart cherry concentrate has a significant benefit for endurance exercise performance.

KEY TEACHING POINTS

- Tart cherry concentrate has a significant benefit for endurance exercise performance.
- Tart cherry concentrate may enhance endurance exercise performance via its low glycemic index, anti-inflammatory and anti-oxidative capacity, and blood flow enhancing effects.

Introduction

Recently, tart cherry concentrate has received growing attention for application in sport as it may be of benefit to performance by increasing muscle function (1–3), inhibiting oxidative stress/inflammation (2–4), and reducing muscle soreness (1,5). The improvement in these four aspects might allow greater recovery from training sessions that lead up to an endurance exercise performance session, thus improving endurance exercise performance. Tart cherry juice might also increase endurance performance by providing sustained energy and facilitating fat oxidation during exercise via its low glycemic index (6), and increasing oxygen delivery to working muscle via its blood flow enhancing effect (7) by increasing nitric oxide (NO) bioavailability (8).

Eccentric exercise-induced mechanical stress damages muscle (9) and impairs muscle function (10). Most studies have shown that tart cherry concentrate consumption decreases the extent of this damage, attenuates strength loss and accelerates recovery after exercise (1–3, 11). Tart cherries might exert these beneficial effects via the prevention of oxidative stress and inflammation (11). Exercise also produces excessive free radicals which disrupts redox balance (12), alters cell signaling and degrades cellular performance (13). Tart cherry concentrate lowers blood markers of oxidative stress after exercise-induced damage whether the exercise involves high-intensity eccentric contractions (2) or endurance exercise (3). Tart cherries are high in anthocyanin, which inhibits cyclo-oxygenase-2 (an inflammation-associated enzyme); this might contribute to the anti-inflammatory effect of tart cherry concentrate (14). Interleukin-6 and C-reactive protein are reduced following a marathon run (3) and prolonged, intermittent exercise (4) with tart cherry concentrate consumption, compared to placebo. In contrast, tart cherry concentrate supplementation did not affect high-sensitive C-reactive protein after knee extensions, compared to placebo (2). Anthocyanins derived from tart cherries suppressed inflammation-induced pain in rats and this pain-inhibiting effect found in tart cherries was similar as indomethacin (15). Several human studies also reported reduced pain scores with tart cherry concentrate supplementation after eccentric elbow flexion contractions (1) and a long distance relay race (5); while one study did not find this pain-reducing effect in marathon runners (3).

Although the potential role of tart cherry concentrate in these four categories (i.e., muscle function, oxidative stress, inflammation and muscle soreness) has been widely studied, studies are mixed on whether tart cherries provide...
an endurance exercise performance benefit (7,16–19). For example, tart cherry concentrate supplementation reduced half-marathon race finish time in 11 triathletes and endurance-trained runners (18), improved 15-km cycling time trial performance in 8 trained male cyclists (7), enhanced end-sprint performance (i.e., peak power over the first 20 seconds and total work completed during a 60-second all-out sprint) in 10 trained cyclists, compared with a placebo condition (16), but did not affect the time to exhaustion for a cycling test in 10 trained cyclists (16) and did not influence the performance test in 9 male Water Polo athletes (i.e., distance in Water Polo intermittent shuttle test) (17) and 12 recreational cyclists (i.e., 10 km time trial) (19), compared with placebo conditions. Small sample sizes, typical of exercise performance research (7, 16–19), limits making conclusions about effectiveness. A meta-analysis is therefore needed to overcome this problem of low statistical power. Our purpose was to investigate the effects of tart cherry concentrate on endurance exercise performance by performing a meta-analysis of intervention studies. Clarification of the potential performance-enhancing effects of tart cherry concentrate will enable recommendations for athletes to be determined more confidently.

**Method**

**Search Strategy**

A literature search was conducted up to November 30, 2019 using Medline, Embase, Web of Science and Google Scholar. The search strategy is shown in Figure 1. Terms used for the search combined terms related to cherries (tart cherry juice; TC juice; Montmorency; cherry; cherries) and sport performance (exercise; competition; performance; sport; sport performance). We also searched reference sections of retrieved articles for additional articles. Exclusion/inclusion criteria were identified using the acronym "PICOS": population (i.e., healthy adults), intervention (i.e., tart cherry supplementation), comparator (i.e., placebo), outcomes (i.e., endurance exercise performance) and study type (i.e., randomized controlled design). Two reviewers reviewed studies for inclusion at each stage (Figure 1) and any disagreement was resolved by discussion between the two reviewers.

**Quality assessment**

The risk of bias was assessed by two reviewers using the modified Cochrane Collaboration tool which covers bias in
six domains: selection bias (source of bias: random sequence generation and allocation concealment), performance bias (source of bias: blinding of participants and personnel), detection bias (source of bias: blinding of outcome assessment), attrition bias (source of bias: incomplete outcome data), reporting bias (source of bias: selective reporting), and other bias (other sources of bias specific to the study) (20).

Data extraction

Data extracted included either performance change scores or standard deviations after tart cherry concentrate (and placebo) ingestion for nine studies (3, 7, 16, 18, 19, 21–24) or presupplementation and post-supplementation (cherry juice and placebo) performance means and standard deviations for one study (17). When pre and postsupplementation means were extracted, change scores were calculated as presupplementation mean subtracted from postsupplementation mean. Standard deviations (SD) for the change scores were estimated from pre and postsupplementation standard deviations (SDpre and SDpost) using the following equation derived from the Cochrane Handbook for Systematic Reviews of Interventions:

\[
\text{SD change score} = \left( (\text{SDpre})^2 + (\text{SDpost})^2 - 2 \times (\text{correlation between pre- and post-scores}) \times \text{SDpre} \times \text{SDpost} \right)^{1/2}
\]

In this equation we used 0.8 as the assumed correlation between pre and postscores.

Data analyses

A meta-analysis was run using RevMan 5 software. Heterogeneity was evaluated using \(\chi^2\) and I\(^2\) tests where heterogeneity was indicated by either \(\chi^2\) p-value equal or less than 0.1 or I\(^2\) test value greater than 75%. Heterogeneity was not present and therefore we used a fixed-effects model for our meta-analysis. As units of measurement differed across studies we calculated standardized mean differences and 95% confidence intervals. Measurements included change in distance on a shuttle swimming test (17), time to exhaustion on high-intensity cycling tests (16,24), total work performed during cycling (21,22), time to complete a full marathon (3), a half marathon (18) and three cycling time trials (10 km, 15 km and 20 km) (7,19,23). To ensure that all performance changes were in a positive direction for beneficial effect, we converted the time to cover the full and half marathon and time to cover 10 km, 15 km and 20 km cycling to velocity (i.e., km/min). A forest plot was generated for study-specific standardized mean differences along with 95% confidence intervals and pooled effects. A p-value of 0.05 or less was considered statistically significant. A funnel plot was generated to see if there is a publication bias. The funnel plot is used to visually assess publication bias via its asymmetry. Each dot represents an individual study. If the studies are unbiased, the plot would be symmetrical (i.e., all the studies fall within the boundaries indicated by the dashed lines representing the borders of an inverted funnel). If the studies are biased, the funnel plot would become asymmetrical (i.e., any studies that are biased fall outside the boundaries indicated by the dashed lines).

Results

Selection of studies

After exclusion by title and abstract, eight potential articles were identified. A further three articles were included after reading the full manuscript, as they included performance scores in the manuscript text, but not in the title or abstract (3,21,22). To be included, studies were required to assess aerobic endurance performance; this resulted in exclusion of one additional article. Participant characteristics, supplementation protocols and exercise performance tests for each study included are shown in Table 1. One study involved only the same-day supplementation while all the other studies involved chronic supplementation.

Methodological quality

Generation of the randomization sequence and allocation concealment was adequate in only one study (19) and unclear in the remaining nine studies (Table 2). Only one study did not provide information for blinding of participants and researchers. The other nine studies used a double-blind design (Table 2). In one study, attrition was higher in the tart cherry arm than the placebo arm, resulting in imbalance in numbers between arms (18). Attrition was the same between arms in the remaining nine studies (Table 2). Results were fully reported in the ten studies, so these studies are at low risk of reporting bias (Table 2). The funnel plot (Figure 2) showed there is no publication bias.

Meta-analysis

Significant endurance exercise performance-enhancing effects were reported with tart cherry concentrate consumption in 2 of the 10 studies included (7,18). The pooled effect across the 10 studies indicated a significant improvement in endurance performance with tart cherry concentrate supplementation (standardized mean difference: 0.36; 95% CI: 0.07 to 0.64; \(p = 0.01; I^2=0\%\); Figure 3).

Discussion

This is the first meta-analysis evaluating the effect of tart cherry concentrate on endurance performance. This review indicates significant ergogenic benefit of cherry consumption. The importance and practical application of this meta-analysis is that this will inform athletes of the use of tart cherry concentrate as an effective supplementation strategy to improve endurance exercise performance.

Potential mechanisms for performance-enhancing effects

Theoretically, tart cherry concentrate may enhance endurance exercise performance via its low glycemic index, anti-
<table>
<thead>
<tr>
<th>Study</th>
<th>Study design</th>
<th>Population</th>
<th>Washout period</th>
<th>Tart cherry supplement</th>
<th>Placebo</th>
<th>Timing</th>
<th>Exercise performance</th>
<th>Change scores</th>
<th>Change scores</th>
<th>Significant effect reported?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Howatson 2010 Pseudorandomised, placebo-controlled, parallel</td>
<td>20 recreational marathon runners, 13 males, 7 females</td>
<td>NA</td>
<td>Two bottles of tart cherry juice blend (8 oz for each bottle, containing at least 40 mg anthocyanins)</td>
<td>Two servings of fruit flavored concentrated fruit juice bland containing 8 oz of water per day</td>
<td>5 days before, on the day of and 2 days after a Marathon run</td>
<td>Marathon finish time (min)</td>
<td>3:48:04 ± 0:48:58</td>
<td>4:15:48 ± 1:01:22</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Clifford 2013 Counter-balanced, double-blind, placebo-controlled, crossover</td>
<td>9 male cyclists or triathletes, 32 ± 112 years, V02max 42.0 ± 8.6 L/min, 4.2 ± 0.7 L/min</td>
<td>At least 5 days</td>
<td>200 mg capsules per day containing 216 mg polyphenols</td>
<td>200 mg capsules per day</td>
<td>3 consecutive days: 2 days before and on the day of exercise</td>
<td>20km cycling time trial (s)</td>
<td>2008.56 ± 97.50</td>
<td>2010.30 ± 124.73</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Bell 2014 Randomized, double-blind, placebo-controlled, parallel</td>
<td>16 well-trained male cyclists, 30 ± 8 years, V02max 616 ± 10.4 mL/kg/min</td>
<td>NA</td>
<td>30 mL concentrate (9.117 mg/mL anthocyanins) mixed with 100 mL water, twice per day</td>
<td>30 mL cordial mixed with 100 mL water and maltodextrin, twice per day</td>
<td>7 consecutive days: 4 days pre-trial and on each trial day (3 trials)</td>
<td>Mean work performed over 3 cycling trials (kJ)</td>
<td>146.49</td>
<td>142.29</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Bell 2015 Stratified randomization (based on VO2peak), double-blind, placebo-controlled, parallel</td>
<td>16 well-trained male cyclists, 30 ± 8 years, V02max 616 ± 10.4 mL/kg/min</td>
<td>NA</td>
<td>30 mL concentrate (9.2 mg/mL anthocyanins) mixed with 100 mL water, twice per day</td>
<td>30 mL cordial mixed with 100 mL water and maltodextrin, twice per day</td>
<td>8 consecutive days: 4 days pre-exercise, on the day of and 3 days postexerci</td>
<td>Total work performed during cycling (kJ)</td>
<td>155.1 ± 23.6</td>
<td>151.3 ± 27.9</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Levens 2016 Randomized, double-blind, placebo-controlled, parallel</td>
<td>27 endurance-trained runners or triathletes, 18 males, 9 females, 218 ± 3.9 years</td>
<td>NA</td>
<td>Powdered tart cherries 480 mg/day (~66 mg anthocyanins) in capsule form (n = 11)</td>
<td>Rice flour 480 mg/day in capsule form (n = 10)</td>
<td>10-day supplementation: 7 days before, on the day of and 2 days after marathon race</td>
<td>Half-marathon finish time (min)</td>
<td>103 ± 9.28</td>
<td>118 ± 9.72</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>McMormick 2016 Randomized, double-blind, placebo-controlled, crossover</td>
<td>9 highly trained male water polo athletes, 18 ± 1.4 years</td>
<td>5 weeks</td>
<td>90 mL tart cherry juice concentrate/day (9.17 mg/mL anthocyanins) diluted with water into 600 mL</td>
<td>120 mL cordials mixed with 480 mL water</td>
<td>6 conclusive days before the testing day</td>
<td>Water Polo Intermittent Shuttle Test-distance (m)</td>
<td>Prescores 655 ± 261</td>
<td>Postscores 605 ± 239</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Keane 2018 Randomized, double-blind, placebo-controlled, crossover</td>
<td>10 highly trained male cyclists, 28 ± 7 years, VO2peak 590 ± 7.0 mL/kg/min</td>
<td>3–7 days</td>
<td>60 mL of commercially available Montmorency tart cherry concentrate/day (7.350 mg/L cyanidin-3 glucoside) diluted with 100 mL 300 mL tart cherry juice/day (9.2 mg/mL anthocyanins) for 4 days before and 2 days after exercise: 1g/kg body weight carbohydrate in the form of tart cherry juice</td>
<td>300 mL sports drink/day for 4 days before and 2 days after exercise: 1g/kg body weight carbohydrate in the form of sports drink</td>
<td>15 hour before performance tests</td>
<td>Time to exhaustion for cycling test (s)</td>
<td>772 ± 34</td>
<td>733 ± 34</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Gao 2018 Randomized, counterbalanced, double-blind, placebo-controlled, crossover</td>
<td>12 recreational cyclists, 8 males, 4 females, 34 ± 15.8 years, VO2peak 382 ± 7.4 mL/kg/min</td>
<td>1 month</td>
<td>300 mL tart cherry juice/day (9.2 mg/mL anthocyanins) for 4 days before and 2 days after exercise</td>
<td>300 mL sports drink/day for 4 days before and 2 days after exercise</td>
<td>7-day supplementation: 4 days before, on the day of and 2 days after exercise</td>
<td>10 km cycling time trial (min)</td>
<td>17 ± 3</td>
<td>17 ± 2</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Davis 2019 Randomized, counterbalanced, double-blind, placebo-controlled, crossover</td>
<td>20 recreationally active men, 27.8 ± 22.6 years, VO2peak 4005 ± 2.87 mL/kg/min</td>
<td>1 week</td>
<td>500 mg freeze dried tart cherry powder per day</td>
<td>500 mg powdered cellulose per day</td>
<td>8 consecutive days: 7 days before and on the day of exercise</td>
<td>Time to exhaustion for cycling test (min)</td>
<td>18.40 ± 1.48</td>
<td>17.16 ± 1.78</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Morgan 2019 Randomized, counterbalanced, double-blind, placebo-controlled, crossover</td>
<td>8 highly trained male cyclists, 19 ± 16 years, VO2peak 623 ± 10.1 mL/kg/min</td>
<td>At least 2 weeks</td>
<td>6 Montmorency tart cherry powder capsules daily (256.8 mg/day of anthocyanins)</td>
<td>6 Dextrose powder capsules daily</td>
<td>7 days in total: 3 pills in the morning and evening for 6 days before the testing day; on the testing day, 3 pills 1 hour before tests</td>
<td>15-km cycling time trial (s)</td>
<td>1506 ± 86</td>
<td>1580 ± 102</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>
inflammatory and anti-oxidative capacity, and blood flow enhancing effects. Tart cherry juice has a low glycemic index (GI = 45) (6). Low glycemic index foods induce slower and smaller increase in postprandial blood glucose and insulin levels (25). Low glycemic index foods consumed before exercise may improve endurance performance by maintaining carbohydrate availability during exercise (25). The sustained release of glucose into blood after slow digestion of low glycemic index foods provides sustained energy during exercise, which is important in the later stages of prolonged exercise. Also, insulin inhibits fat oxidation and promotes glucose utilization (26–28); therefore, the attenuation of post-prandial insulinemia may facilitate fat oxidation and reduce the depletion of muscle glycogen (29). This altered fuel utilization may contribute to enhanced endurance performance.

Table 2. Methodological quality of included studies.

<table>
<thead>
<tr>
<th>Study</th>
<th>Random sequence generation (selection bias)</th>
<th>Allocation concealment (selection bias)</th>
<th>Blinding of participants and researchers (performance bias)</th>
<th>Blinding of outcome assessment (detection bias)</th>
<th>Incomplete outcome data (attrition bias)</th>
<th>Selective reporting (reporting bias)</th>
<th>Other bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Howatson 2010</td>
<td>Unclear</td>
<td>Unclear</td>
<td>Unclear</td>
<td>Unclear</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
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<tr>
<td>Clifford 2013</td>
<td>Unclear</td>
<td>Unclear</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
</tr>
<tr>
<td>Bell 2014</td>
<td>Unclear</td>
<td>Unclear</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
</tr>
<tr>
<td>Bell 2015</td>
<td>Unclear</td>
<td>Unclear</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
</tr>
<tr>
<td>Levers 2016</td>
<td>Unclear</td>
<td>Unclear</td>
<td>Low risk</td>
<td>Low risk</td>
<td>High risk</td>
<td>Low risk</td>
<td>Low risk</td>
</tr>
<tr>
<td>McCormick 2016</td>
<td>Unclear</td>
<td>Unclear</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
</tr>
<tr>
<td>Keane 2018</td>
<td>Unclear</td>
<td>Unclear</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
</tr>
<tr>
<td>Gao 2018</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
</tr>
<tr>
<td>Davis 2019</td>
<td>Unclear</td>
<td>Unclear</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
</tr>
<tr>
<td>Morgan 2019</td>
<td>Unclear</td>
<td>Unclear</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
<td>Low risk</td>
</tr>
</tbody>
</table>

Figure 2. Funnel plot indicating whether or not there is a publication bias.

Figure 3. Forest plot showing the effects of tart cherry concentrate on endurance exercise performance. Diamond represents the pooled effect.
Tart cherries contain many phytochemicals such as anthocyanins, flavonoids, flavanols, gallic acid equivalents, and phenolic acids. These anti-inflammatory and antioxidant compounds have been shown to decrease muscle damage, reduce pain and improve recovery after intense exercise in athletes (14). Exercise-induced excess reactive oxygen species impairs redox-sensitive calcium handling, damages muscle membrane, reduces muscle contractile force output and therefore impairs exercise performance (30). Tart cherry juice has the potential to improve exercise performance by reducing oxidative stress and rebalancing redox via its antioxidant capacity. This has been supported by many studies where blood markers of oxidative stress/inflammation were significantly attenuated after exercise with tart cherry juice consumption, compared with placebo (3, 4).

Recent studies found that the tart cherry supplementation increased muscle oxygenation during exercise (7) probably via: (1) the nitric oxide (NO) pathway by increasing NO bioavailability through inhibiting nicotinamide adenine dinucleotide phosphate oxidase (8); and (2) cyanidin-3-glucoside (an anthocyanin high in tart cherries)-induced decrease in the expression of inducible NO synthase (31) and increase in endothelial NO synthase expression (32). This altered balance between inducible NO synthase and endothelial NO synthase would further favor vasoactive NO bioavailability (8), thus inducing vasodilation, increasing blood flow, and increasing oxygen delivery to the working skeletal muscles, which is an important factor affecting exercise performance. The increased perfusion and blood flow would also facilitate the efflux of exercise-induced metabolic waste, thus further maintaining muscle function during exercise and increasing exercise performance.

Potential factors affecting results

Among the 10 studies included, only 2 studies reported significant performance-enhancing effects with tart cherry juice supplementation (7,18), while the others were unable to find this. Although most studies showed no effect, the pooled effect from this meta-analysis showed significant benefits. Potential factors that might affect the study results are participant demographic, diet/exercise control, supplementation protocol and measurements for exercise performance.

Most of the studies used males only and 3 of 10 studies in this meta-analysis included both males and females. Average ages ranged from 18.6 to 34.6 years old. Most of the studies involved endurance-trained individuals, i.e., cyclists, runners or triathletes. Only one study employed Water Polo athletes and no differences were found for performance measures in this study. This could be due to the intermittent and un-weighted nature of the performance which was done in water. Water polo exercise might cause a lower mechanical strain than that caused by cycling or endurance running efforts (17). This lower mechanical strain might induce a smaller degree of inflammation (33), thus potentially lessening the effects of a supplement that is supposed to offset inflammation. Land-based prolonged endurance exercise, such as running and cycling, might elicit a greater muscle damage and inflammation. Therefore, studies on cherry-based products might be of value to athletes in these fields. Also, this study used a fruit juice as placebo, which may also contain beneficial anti-oxidants. Participant fitness level might be another important confounder. Performance-based trials typically use well-trained athletes, because the coefficients of variation for them are often lower than that in untrained or recreationally active participants, thus achieving consistent performance across trials and providing a greater chance of detecting significant results (34). Also, well-trained participants may rely less on carbohydrate oxidation during prolonged endurance exercise because their fat oxidation capacity is greater, compared with untrained or recreationally active participants (35). According to the thresholds for very well-trained participants (VO2max >55 ml/kg/min for women and >65 ml/kg/min for men) and trained participants (VO2max >40 ml/kg/min for women and >55 ml/kg/min for men) (36), most of the studies used trained or well-trained participants (3,7,16–18,21–23). The other studies included in this meta-analysis used recreationally active individuals (19,24). The study that showed the lowest improvement with cherry juice out of all the studies (19) had the lowest training level of the participants involved (VO2peak: 38.2 ± 7.4 ml/kg/min).

Only two studies did not control diet (3,17), whereas in the other studies, participants were under diet control by writing food diaries and/or adhering to food restrictions. More specifically, during the dosing period, participants were usually required to adhere to a low-polyphenolic diet with avoidance of vegetables, fruits, grains, cereals, whole-meal bread, alcohol, coffee, tea, vitamin supplements and chocolate because these foods contain some of the same beneficial ingredients as the cherry juice (16,19,21–23). Also, participants were instructed to not change their dietary habits in any way throughout the study and write 1 to 8 day food diaries during the dosing period to make sure they consumed the same food for each trial. In one placebo-controlled, parallel design study, participants were instructed to not change their eating habits, but there were no food restrictions and there might be large differences in food choices between cherry and placebo groups, which might affect the results (18). In some studies, participants were also required to refrain from strenuous exercise during the dosing period (19,23). The lack of diet control or exercise control in some studies might be confounding variables.

As for the supplementation protocol, most studies employed a loading phase of around 2 to 7 days prior to the exercise performance session (11). The peak time for anthocyanins is about 2 hours after consumption and by 8 hours, anthocyanins will be cleared from blood (11). Therefore, a pre-exercise consumption about 2 hours before an exercise event is suggested (11). Unlike the other studies that continued to provide tart cherry juice 1 and 2 hours before exercise, participants in McMormick’s study did not consume tart cherry juice on the performance testing day (17). This might be a reason they failed to find a beneficial effect of tart cherry juice.
Finally, variations among different tests might affect the results. These 10 studies used different measurements to assess endurance exercise performance, i.e., time to exhaustion on high-intensity cycling tests, half-marathon finish time, full marathon finish time, 15-km cycling time trial, 10-km cycling time trial, 20-km cycling time trial, work performed during cycling and distance on a Water Polo Intermittent Shuttle Test. Half of the studies used time trial which has lower coefficients of variation (34) and therefore is more robust.

**Supplementation strategy: dosage, timing and types of supplements**

Many human exercise studies have successfully found beneficial effects of tart cherry supplementation; however, little rational has been provided for the supplementation protocol, and an optimal strategy is not known. Supplementation form, dosage and timing vary widely. The supplementation forms used in these studies were tart cherry powder, tart cherry powder capsules, tart cherry juice and most commonly tart cherry juice concentrate. The loading phase in these studies ranged from 2 to 7 days before, on the day of, and 2–4 days after exercise. On the exercise day, tart cherry supplementation is usually consumed approximately 2 hours before exercise because anthocyanin bioavailability (the main flavonoid in tart cherries) increases to a peak between 1 and 2 hours after ingestion (37). The dosages used in these studies were: (1) 200–500 mg/day in either capsule form or powder form containing 66–256.8 mg/day of anthocyanin; (2) 60 to 90 mL/day cherry juice concentrate containing approximately 9.117 mg/mL of anthocyanins (a 30 mL concentrate contains approximately 90–110 tart cherries) diluted with 100–510 mL water; and (3) 300–473 mL/day in cherry juice form, equivalent of approximately 90 to 120 tart cherries daily, containing at least 80 mg anthocyanins. The concentrate and juice blend were usually split into two boluses and consumed twice a day (taken morning and afternoon). The total amount of anthocyanins consumed per day across the studies ranged from 66 to 2760 mg. Only two studies reported significant performance-enhancing effect and they used lower anthocyanin amounts, i.e., 66 mg (18) and 256.8 mg (7), whereas other studies with a higher anthocyanin dosage (e.g., 821 mg (17) and 2760 mg (19)) had smaller effects according to Figure 3. Also, another chronic-supplementation trial with greater effect used a lower anthocyanin dosage of at least 80 mg per day (3). A suggested amount of anthocyanin (derived from purple carrot juice) ranged from 65 to 323 mg (38), because anthocyanin absorption mechanisms might be saturated at high dosage (39). However, this might not be generalizable to all plants containing anthocyanins because the plant matrix may affect metabolism and bioavailability (38). For the studies included in this meta-analysis, there was no "dose-response" relationship, i.e., higher doses of cherry juice supplementation did not induce a greater effect, according to the forest plot (Figure 3). Interestingly, studies with only the same-day supplementation (16) showed better effects than studies that involved chronic supplementation (Figure 3). Clearly, studies are warranted to find an optimal supplementation strategy.

**Conclusion**

This meta-analysis shows a significant improvement in endurance performance with tart cherry consumption. Tart cherries may exert this beneficial effect via its low glycemic index, anti-inflammatory/anti-oxidative capacity, and blood flow enhancing effects.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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