Abstract: Rock climbing is a fast-growing sport. Nutritional recommendations for climbing performance remain limited. In a sport where reduced fuel availability/dehydration could result in declined performance and fatal error, nutrition is key to a successful climb. Elite rock climbers are typically lean and small in stature. Climbers exhibit a lower aerobic capacity than other elite athletes of similar body composition, i.e., endurance athletes. Heart rates while climbing can be disproportionately high due to isometric muscle contractions, hands in overhead positions, and the psychological stress of climbing at height. The typical rate of energy expenditure is 10–11 kcal/minute while climbing. Carbohydrate needs are estimated at 3–7 g/kg body mass (BM)/day. Fluid intakes of ~250 mL/hr water or sports drink are recommended to prevent dehydration, but should be individualized based on sweat rate and climbing environment. Competitions that require climbing multiple routes within quick succession demand the rapid replenishment of depleted muscle glycogen stores. Nutrition in competitive adolescent climbers should support growth and performance. This population is strongly encouraged to seek advice from board certified or registered nutrition experts, particularly when weight loss is a desired outcome. Future research in rock climbers is warranted across all aspects of sport nutrition, as summarized in this review.

Keywords: energy availability; adolescents; diet; sport climbing; lead climbing; speed climbing; bouldering
1. Introduction

Rock climbing is a new and fast-growing sport. Organized competition gained momentum in 1985 after a formalized outdoor competition hosted in Italy and the addition of youth climbing in 1992 (“International Federation of Sport Climbing: About the IFSC”, 2019). The sport continues to grow in popularity with the number of indoor rock climbing gyms increasing on a yearly basis. As a result, The International Federation of Sport Climbing (IFSC) was formed in 2007 and competitive rock climbing is now recognized globally. This popular sport is poised to take a prominent position on the world stage with its debut in the 2020 Olympic games in Tokyo (“IOC Approves Five New Sports,” 2016).

Athletes with impairments, termed paraclimbers or adaptive climbers, also participate in formalized competitions. Competitions take place indoors and outdoors on artificial walls in order to standardize the difficulty of the climb and ensure a level playing field for all competitors. The 2016 IFSC Championships hosted in Paris involved 533 able-bodied athletes and 77 adaptive athletes from 53 countries (“IFSC World Championships: Key Figures,” 2018). The average age of an IFSC athlete is 23, with women representing 40% of the athletes (“IOC Buenos Aires Youth Olympic Games,” 2018).

Climbers face an array of nutritional, physiological and psychological challenges. Optimizing power-to-mass ratio (rate of work or force × velocity at a given body mass), delaying muscular fatigue, and promoting recovery are top priorities from a physiological standpoint. Heavier climbers require greater strength to maintain contact with holds, which increases the workload for the overall route (Watts, 2004). Outdoor climbers face additional physical and psychological challenges, including variations in altitude, humidity, wind conditions, and a greater psychological stress from climbing at heights not experienced during indoor climbing. At present, the body of knowledge used to inform nutritional recommendations for competitive rock climbers, indoors or outdoors, is limited to one published review paper (Smith, Storey, & Ranchordas, 2017). Given that rock climbing has recently been added to the Olympic portfolio, this timely review will focus on nutritional considerations for training and competition for the three official competitive events in rock climbing, namely bouldering, lead climbing, and speed climbing.

2. Competitive events in rock climbing

The three rock climbing events that will be included in the 2020 Tokyo Olympics are bouldering, lead climbing and speed climbing. These three disciplines are combined into one competition for the podium in sport climbing’s Olympic debut. The competitors are scored based on a point system based on how they climb the route. In brief, bouldering refers to climbing up to six meters high, typically in a traverse horizontal movement pattern without rope or harness. Typically, a combination of ~10 moves are completed within four minutes. Lead climbing employs a belayer on the ground and a climber on the rock wall. Rather than the rope being threaded through a top anchor, the climber must thread the rope through fixed anchors along the route. This process takes extra skill, energy, mental acuity, and hand/finger strength to guide the rope as one climbs. Competitive lead climbing routes are typically 15 m high and need to be completed, called “sending” within 8 minutes (semifinals) or 6 minutes (finals). Finally, speed competitions are held on a 15 m wall with standardized holds along the route, in order to validate world record times. Speed climbing utilizes top rope method where the climber is attached to an auto-belay mechanism. The climber must ascend as fast as possible against an opponent climbing at the same time on an adjacent route. These routes are often completed in less than 10 seconds at the elite level.

Climbing difficulty is rated based on the types of moves required of the climber to complete (called “sending”) a route. The more challenging the moves, the higher the difficulty. The International Rock Climbing Research Association (IRCRA) has proposed a unified rating system for route difficulty into five categories: Lower Grade, Intermediate, Advanced, Elite, and Higher Elite.
3. Rock climbing training

Training for rock climbing competition can vary greatly, depending on the climber’s individual training goals and periodized training plan, as well as the difficulty level and duration of competition itself. These variables mean that devising nutrition recommendations to meet the physiological demands of rock climbing is complex and explain, at least in part, the current dearth of established nutrition recommendations for rock climbing.

Competitions take place at local, regional, national, and international levels. Competitions may last one or multiple days, but climbers must ascend four or more routes within that day, taking less than four minutes to complete each climb. The timing of climbs within the same competition also varies. A climber can be at the competition venue for several hours and, during this time, can have long periods of rest. These rest periods typically take place in “isolation” where climbers are hidden from view of the routes and other climbers, so they may not gain an unfair advantage.

Rock climbing is unique in that no true off-season exists. Many climbers train and compete year-round. As a result, nutrition recommendations should be individualized according to training cycles (strength, endurance, or competition), climbing goals, and anthropometric goals. Competitive climbers aiming for the World Cup, World Championship, and Olympic venues should prioritize and periodize their nutrition and training goals to coincide with these events.

4. Anthropometrics of rock climbers

Prior to devising nutritional recommendations for competitive climbers, it is important to understand the anthropometric profiles of rock climbers and the physiological demands of elite climbing. Elite rock climbers are typically shorter, leaner, and lighter than non-climbing athletes, with similar anthropometric profiles to ballet dancers and long-distance runners (Booth, Marino, Hill, & Gwinn, 1999; Sheel, 2004; Watts, Martin, & Durnschi, 1993). Elite climbers often report a high “ape index,” which describes the ratio of arm span to height (Mermier, Janot, Parker, & Swan, 2000). These observations have been verified in both children and elite adult climbers (Macdonald & Callender, 2008; Watts et al., 1993). In a cohort study that compared 90 youth (mean age: 13.5 years) climbers with non-climber controls, Watts et al. (Watts, Joubert, Lish, Mast, & Wilkins, 2003) reported a smaller stature (climber: mean = 159 cm, control: mean = 167 cm), lower body mass (climber: mean = 48 kg, control: mean = 54 kg), less body fat as measured by sum 9 of skinfolds (climber: mean = 67 mm, control: mean = 101 mm), and greater handgrip-to-body mass ratio (climber: mean = 0.67, control: mean = 0.55) in climbers. Moreover, expressed relative to body mass index (BMI), youth climbers exhibited greater lean mass than controls. However, this study did not address puberty status (Watts et al., 2003) and thus future study is warranted to determine the anthropometric profiles of rock climbers throughout adolescents. Similarly, elite adult climbers reported a short stature, low body mass, and low body fat using the sum of skinfolds than controls (Booth et al., 1999; Watts, 2004; Watts et al., 1993). Indeed, body fat was measured at 4–14% for men and 10–20% for women among semifinalists at a World Cup competition (Sheel, 2004) via sum of seven skinfolds. Whereas a high power-to-mass ratio is commonly considered advantageous in rock climbing (Booth et al., 1999; Watts et al., 1993), one study demonstrated that the training history of climbers (e.g. years training) better predicted competition level than anthropometric profile (Mermier et al., 2000). With more recent competitions including routes with more overhangs, future research on climbers’ anthropometrics are warranted. Comprehensive data on anthropometric profiles of climbers have been summarized elsewhere (Mladenov, Michailov, & Schöffl, 2001; Morrison & Schöffl, 2007).

Elite rock climbers anecdotally report losing weight in order to send harder routes. Such weight loss activities position climbers at risk of restrictive eating patterns (Zapf, Fichtl, Wielgoss, & Schmidt, 2001), thus increasing the potential for eating disorders, disordered eating, laxative/diuretic use and Relative Energy Deficiency in Sport (RED-S) (Watts, 2004; Zapf et al., 2001). To discourage anorexia and disordered eating behavior, the Austrian Sportclimbing Organisation banned competitors with a Body Mass Index ≤17 and others (Lutter, El-Sheikh, Schöffl, & Schöffl, 2017) have expressed concern over the possibility of anorexia athletica, particularly in young
climbers. Sundgot-Borgen and Garthe (2011) reports a 40–42% prevalence of eating disorders for females in aesthetic sports, 17–18% for males in aesthetic sports, and 30–35% prevalence for females in weight-class sports and 22–42% for males in gravitational sports.

5. Physiological requirements of rock climbing

5.1. Energy expenditure
A logical starting point for devising evidence-based nutrition recommendation in any sport is to characterize typical levels of energy expenditure. The energy expenditure of rock climbers has been studied in a variety of settings, with average energy expenditure values for outdoor climbers recorded at ~10–11 kcal/min of climbing (Watts, 2004). During training and competition, energy expenditure can vary depending on the type and difficulty of climb (Dickson, Fryer, Blackwell, & Draper, 2012; Watts, 2004). Energy expenditure values of easy and difficult routes were recorded at 9 kcal/min and 13 kcal/min, respectively (Mermier, Robergs, McMinn, & Heyward, 1997). Estimated energy expenditure also has been shown to increase with increasing angle of climb by 1.5–2.0 extra kcal/min at 80–90°angle climbs, and 5 extra kcal/min at 102° climbs (Watts, 2004). In contrast, energy expenditure has been shown to decrease with repeated ascents and route familiarity (España- Romero et al., 2012; Watts, España- Romero, Ostrowski, & Jensen, 2019). Although the physiological relevance of these differences in energy expenditure remain unclear, from a performance perspective, a faster ascent does mean beating an opponent in speed climbing.

5.2. Energy systems in rock climbing
Understanding the predominant energy systems utilized during rock climbing will help to determine nutrition recommendations. Two key pre-requisites of rock climbing performance are muscle endurance and power during isometric and dynamic movement patterns (Sheel, 2004). Depending on climbing route, there can be periods of slow climbs with low intensity activity, isometric contractions, and periods of rest on the wall. These movements are interspersed with brief explosive efforts to propel the climber’s body upward or sideways to grip the next hold, sometimes even jumping to achieve this. These movements demand strong forearm and finger strength, handgrip force and finger force, and shoulder girdle contraction with very little demand on lower body muscle groups (Bertuzzi, Franchini, Kokubun, & Kiss, 2007; Sheel, 2004; Watts et al., 1993). A high aerobic capacity in climbing is less crucial than other sports such as running or cycling, since climbing is estimated to require ~60% less aerobic power than running (Watts, 2004). A higher aerobic capacity could possibly enhance recovery between ascents, but to the authors’ knowledge this hasn’t been examined and we agree with Watts (2004) suggestion that this would be a worthy future research endeavor. Routes with steeper angles and more difficult terrain require greater levels of anaerobic power (Bertuzzi et al., 2007; Sheel, 2004). Researchers have reported lower blood lactate concentrations (5 mmol/L) during climbing than runners or cyclists, likely because smaller muscle groups such as the forearms are predominantly activated during exercise (Sheel, 2004). While the impact of an increase in blood lactate concentrations on performance has yet to be determined in rock climbers, handgrip force has been shown to decrease with increasing lactate concentrations (Watts, 2004). Interestingly, higher lactate concentrations were reported in outdoor versus indoor climbers, likely due to more frequent isometric contractions and a greater time period spent in isometric holds while outdoor climbing (Booth et al., 1999). These data suggest a greater anaerobic contribution to ATP resynthesis during outdoor climbing (Booth et al., 1999). In addition, greater lactate concentrations have been associated with increasing route difficulty (Booth et al., 1999; Mermier et al., 1997), whereby blood lactate concentrations remained elevated for 20–30 minutes post-climb, depending on the type of recovery employed (Watts, 2004).

5.3. Heart rate and oxygen kinetic responses in rock climbing
As anticipated, elite rock climbers have been shown to exhibit lower heart rate (Baláš et al., 2014; Sheel, 2004) and VO₂ responses (Booth et al., 1999) to climbing exercise compared with recreational climbers. These studies were not conducted in a competitive setting, thus
physiological responses during competition are unknown and may vary. HR values typically range from 129–180 beats per minute (Sheel, 2004), whereas average VO₂ values are 20–30 ml/kg BM/min (4, 18) during climbing activity. Interestingly, several studies in rock climbers also demonstrate that heart rate is disproportionate to oxygen consumption and blood lactate concentrations. Heart rate is often elevated beyond what would be expected for the climber’s oxygen uptake and level of lactate concentration (Booth et al., 1999; España-Romero et al., 2012; Sheel, 2004). This phenomenon is explained by the observation that climbing requires multiple isometric contractions for up to one third of total ascent time (Booth et al., 1999) and because the arms are usually in an overhead position (Sheel, 2004). Interestingly, VO₂ values and lactate concentrations remain elevated for up to 30 minutes post-climbing (Watts, 2004; Watts, Daggett, Gallagher, & Wilkins, 2000). This observation means that the energy demands of rock climbing encompass both energy expenditure during the climb and post-climb recovery (Watts, 2004). Outdoor climbing elicits a higher heart rate response and oxygen uptake than indoor climbing (Booth et al., 1999). Finally, the nature of climbing introduces an element of psychological stress, anxiety, or fear of falling that can further increase heart rate. (Booth et al., 1999; Draper, Jones, Fryer, Hodgson, & Blackwell, 2008; Mermier et al., 1997; Sheel, 2004). Collectively, these physiological requirements should be considered when estimating nutritional requirements of rock climbers and considering competition schedules.

6. Nutrition recommendations for training and competition

6.1. Energy requirements

The evidence that underpins nutritional recommendations in rock climbing is beginning to increase, but at present remains somewhat limited. As such, nutritional recommendations for rock climbers must be extrapolated from other sports with similar physiological requirements. Like many other sports, nutrition should be tailored to the training and competition schedule of the climber, the type of climbing, and overall body composition goals. Since a key pre-requisite for performance in rock climbing is a high power-to-mass ratio, energy intake must be carefully considered to optimize body mass and composition while still fueling effectively for training and competition and avoiding low energy availability (Sundgot-Borgen et al., 2013). For these reasons, nutrition periodization is essential for the elite rock climber. A climber may train heavier but then introduce a moderate energy deficit in order to reduce body weight for a competition.

Anecdotal evidence from popular climbing blogs (Lucas, 2018) suggests that some climbers have taken drastic measures for weight loss, such as extreme energy restriction, ketogenic dieting, and eliminating whole food groups. These nutritional strategies may compromise performance and health (Sundgot-Borgen et al., 2013). Therefore, energy needs should be balanced with energy intake while maintaining optimum body composition and power-to-mass ratio. An energy excess could lead to increased body weight that may compromise performance, while an energy deficit could lead to low energy availability that also could impact health and performance (Mountjoy et al., 2014).

6.2. Fluid intake recommendations

Hydration is crucial to physical and mental performance across all sports. Climbers should remain hydrated to avoid a > 2% loss of body weight (Maughan & Shirreffs, 2008). With more competitions taking place outside on artificial walls, climbers are now subject to wind, heat, humidity, and altitude to simulate climbing on a natural stone crag. Considering weather conditions and altitude will help customise a climber’s fueling strategy. Heat and humidity may increase rate of perceived exertion and compromise performance (Maughan & Shirreffs, 2008). This perceived feeling of exertion can be mitigated by beginning the competition euhydrated, drinking a carbohydrate and electrolyte solution, and preventing a < 2% body mass loss (Maughan & Shirreffs, 2008). Higher altitude venues likely demand increased fluid needs up to 3–5 L/day (Kechikan, 2011).

Rock climbers often restrict fluid intake while climbing in order to avoid a heavy feeling or the need to void their bladder. Some climbing routes require bending the body, heel hooks above the
shoulder, and other twisting moves, similar to gymnasts and other gravitational sports. If hydration status is adequate, rather than ingesting fluid, a carbohydrate mouth rinse may be recommended to improve performance and perceived exertion (Silva et al., 2014). Although most studies regarding carbohydrate mouth rinse have been conducted within an endurance sport setting, this strategy can be effective for intermittent sports at lower intensities (Baker, Rollo, Stein, & Jeukendrup, 2015; Jeukendrup, 2014; Silva et al., 2014) and thus future research in the context of carbohydrate mouth rinse and rock climbing performance is warranted.

6.3. Macronutrient and micronutrient recommendations

6.3.1. Carbohydrate
The carbohydrate requirements of rock climbers are likely less than endurance athletes due to the comparatively low energy demands of climbing. Estimated carbohydrate needs are in the range of ~3–7 g/kg BM/day, and ~20–30 g/h during a climbing session, with a carbohydrate intake of ~5 g/kg BM/day for multiple speed climbing sets (Joubert, Larson, & Weber, 2016). Carbohydrate-containing sports drinks may contribute to this overall daily carbohydrate recommendation. Simple carbohydrates that are readily absorbed and easily digested are advisable before and during active climbing to minimize gastrointestinal distress and maximize fuel availability. Support for this recommendation stems from previous research with intermittent sport activities showing increased exercise capacity with carbohydrate ingestion (Baker et al., 2015). Slower-release carbohydrates containing more fiber, coupled with protein, may be useful in boulderers and lead climbers, especially for an all-day training or competition (Baker et al., 2015). Smith et al. (2017) recommends a carbohydrate intake of 1 g/kg BM immediately prior to competition for boulderers. For multi-day competitions, carbohydrate intake should be optimized to replenish muscle glycogen stores at the end of each day. Carbohydrate recommendations of 0.8–1.2 g/kg BM/hr, and a per serving protein of 0.3 g/kg BM during the early recovery period has been suggested to enhance muscle recovery (Sousa, Teixeira, & Soares, 2014).

6.3.2. Protein
To date, no studies have systematically evaluated protein needs of rock climbers. However, it is reasonable to assume that protein requirements exceed the Recommended Dietary Allowance for normal persons, which is 0.8 g/kg BM/day in the United States (Institute of Medicine, 2005). A higher dietary protein intake may be considered necessary during periods of strength training (Stokes, Hector, Morton, McGlory, & Phillips, 2018). The current protein recommendation for athletes expressed on a per meal/serving basis is 0.30 g/kg BM (Moore, Slater, & Phillips, 2015), which is equivalent to a 20–25 g protein dose (Witard et al., 2013); or a daily protein intake of 1.3–1.7 g/kg BM/day. Dairy protein that is rich in leucine content, provides one example of a preferable food source to enhance the remodeling of new muscle proteins during climbing recovery (Devries & Phillips, 2015).

6.3.3. Fat
Similar to protein recommendations in rock climbing, no data currently exist with regards to dietary fat recommendations. As a general guideline, there is no known reason to recommend fat intakes in excess of guidelines for the general population, which is ~20-35% of total calorie intake, with an emphasis on omega-3 polyunsaturated fats (derived from oily fish) that may be helpful in reducing inflammation and muscle soreness (Jouris, McDaniel, & Weiss, 2011). Table 1 provides a summary of theoretical nutrition recommendations that may be applied to competitive rock climbers.

6.3.4. Micronutrients
It is reasonable to assume that climbers must maintain adequate micronutrient status to avoid deficiency and perform optimally in training and competition. Vitamin D has been postulated to assist in skeletal muscle function, strength, and balance (Hamilton, 2011), all of which are crucial to rock climbing. Vitamin D sufficiency status is defined as serum 25 hydroxyvitamin D concentrations > 30 nmol/L (Holick et al., 2011). Iron supplementation also may be indicated, particularly in iron deficient climbers training and competing at altitude (Govus, Garvican-Lewis, Abbiss, Peeling, & Gore, 2015). A biochemical exam may be conducted to determine individual
### Table 1. Practical Nutrition Tips for Competitive Rock Climbing

| Energy expenditure during climb session | Daily carbohydrate intake | Daily protein intake |
|----------------------------------------|---------------------------|----------------------|
| General training                        | ~10-11 kcal/min           | 3-7 g/kg BW/day       |
|                                        |                           | 1.3–1.8 g/kg BW/day   |
|                                        |                           | 0.3 g/kg BW per meal  |
|                                        |                           | or snack, 3–4 times   |
|                                        |                           | per day               |
| Competition Speed climbing              | Estimated starting point  | 3-7g/kg BW/day        |
|                                        | at ~10-11 kcal/min. More  |                     |
|                                        | research is needed.*      |                      |
|                                        |                           | 1.3 – 1.8 g/kg BW/day |
|                                        |                           | 0.3 g/kg BW per meal  |
|                                        |                           | or snack, 3–4 times   |
|                                        |                           | per day               |
| Competition Lead/Bouldering             | Estimated starting point  | 3-7 g/kg BW/day;      |
|                                        | at ~10-11 kcal/min. More  | ~20–30 g/hr; recovery |
|                                        | research is needed.*      | meal at end of        |
|                                        |                           | competition; mouth    |
|                                        |                           | rinse as required     |
| Youth climbers                          | Fuel for growth and      | Possibly use less CHO |
|                                        | sport                     | than adults           |
|                                        |                           | Follow pediatric      |
|                                        |                           | guidelines for age    |
|                                        |                           | group, growth pattern,|
|                                        |                           | and activity level     |

| Fluid intake during climb session       | Practical Challenges      | Practical tips        |
|----------------------------------------|---------------------------|-----------------------|
| ~250 mL/hr water or sports drink       | Risk of under-fueling and under-hydrating with short climbs | Begin training hydrated and fueled. Use training to test tolerance to foods planned for consumption during competition. |
| ~250 mL/hr water or sports drink       | Risk of over-fueling and over-hydrating with short climbs | Begin climb hydrated and fueled. Consume easily-digestible foods/beverages after competition to optimize recovery and refuel for subsequent climbs. |
| ~250 mL/hr water or sports drink       | Potential for incomplete recovery between climbs | Eat after competition to optimise recovery and refuel for subsequent climbs. Consume easily-digestible foods/beverages |

**BW, body weight.**

*~10-11 kcal/min of active climbing is based on Watts et al. (2000) measured energy expenditure in climbers in a non-competitive situation. More research is needed to determine actual energy expenditure of competitive climbers.*
iron status and if there is a need for supplementation. B-vitamins, including thiamin, riboflavin, niacin, pyridoxine, folate, and $B_12$, are intermediates in carbohydrate metabolism, and play important metabolic roles in neuromuscular function (Woolf & Manore, 2006). Magnesium and zinc also play key roles in enzymatic reactions for energy metabolism (Fogelholm, 2015; Maughan, 1999). Thus, adequate vitamin and mineral intake should be advocated to ensure proper physiologic functions. This is usually achieved by a variety of fruit and vegetable intake, as well as lean proteins and whole grains. An in-depth discussion of all micronutrients and their implication on athletic performance is beyond the scope of this paper. Future research on vitamin D, iron status, or other micronutrients in rock climbers is warranted.

7. Practical strategies for competition
Table 2 illustrates a sample meal plan for multi-event, day-long competition in rock climbing. During competitive events, rock climbers often have periods of rest before competing in their next event. This schedule can lead to situations of overeating or overhydrating, possibly out of boredom or anxiety. This scenario also can lead to under-fueling if a climber is unprepared with portable nutrition and hydration. Timing of nutrition and hydration can be difficult and unpredictable, especially if multiple routes must be climbed, or a climber is competing in multiple climbing disciplines and/or over a series of days. Climbers can address these nutrition problems by having individually packaged, non-perishable snacks and bottled water or sports drinks in their climbing bag in isolation, as well as being aware of when they are expected to compete. Liquid carbohydrates can be useful to provide easily tolerated quick energy in isolation. It is recommended to test all foods in training to avoid gastrointestinal distress during competition.

For competitions lasting several days, rock climbers must maintain optimal nutrition status with minimal recovery time. Proper nutrition and hydration can present a challenge. Recovery on the first day is essential to have successful subsequent days. As both aerobic and anaerobic systems are utilized during climbing (Bertuzzi et al., 2007), glycogen stores must be replenished to achieve optimal performance in a multi-day competition. Fueling throughout competition can help the recovery process with both micronutrient rich carbohydrate and protein foods and/or beverages, as detailed in Table 2).

8. Supplements in rock climbing
Formal competitions sanctioned by the IFSC require that athletes must adhere to World Anti-Doping Agency guidelines for all supplement and drug use (“IFSC Anti-Doping Program,” 2018). In theory, supplements that may be useful to alleviate “pump” or lactate accumulation during rock climbing performance include beta alanine, beet root juice/nitrates, and sodium

| Event                  | Time  | Time Eaten          | Food                                                                 |
|------------------------|-------|---------------------|----------------------------------------------------------------------|
| Breakfast              | 8 am  | Prior to event      | Steel cut oats with walnuts, berries, and milk. Orange juice as a beverage |
| Round 1 climbing       | 10 am | After event         | Pretzels and sports drink                                            |
| Round 2 climbing       | 12 pm | After event         | Peanut butter and jam sandwich on white bread with apple slices. Chocolate milk as a beverage |
| Round 3 climbing (isolation) | 3 pm | Eat/drink as needed in isolation | Sports gummies and sports drink. Carbohydrate mouth rinse if well-hydrated. |
| Round 4 climbing       | 5 pm  | Prior to event as required | Raisins and sports drink                                             |
| Dinner                 | 7 pm  | After event         | Quinoa bowl with black beans, salsa, cheese, avocado, and ground beef with a fruit and yogurt smoothie |

*Food and beverage quantities vary based on age, body weight, number of rounds, and discipline
bicarbonate. Creatine is a supplement commonly recommended for high-intensity, intermittent activities and resistance training (Arciero et al., 2001; Jäger, Purpura, Shao, Inoue, & Kreider, 2011). In theory, while creatine ingestion may assist in powerful movements necessary for rock climbers the fluid retention of ~0.5–1 L (Jäger et al., 2011) that accompanies a creatine loading regimen may negate any performance benefits experienced by the climber. If a climber chooses to employ creatine, a creatine monohydrate loading protocol of 20 g/day over 5 days may be used, and then switch to a maintenance dose of 3–5 g/day (Rawson, Miles, & Larson-Meyer, 2018) and test for tolerance and performance prior to competition.

Finally, caffeine ingestion helps maintain exercise intensity during an energy deficit, leading to improved cognitive function and mood state. The recommended caffeine dose is 3 mg per kg body weight, or ~200 mg total (Spriet, 2014). In a sport where mental judgement is crucial for safety, caffeine may be an effective supplement. However, the phenomenon of heart rate being elevated beyond normal exertion also should be considered. To our knowledge, no data exist to support or refute the use of caffeine in rock climbing.

9. Nutritional considerations for adolescents
Adolescent rock climbers are commonly involved in elite level competition. Sport climbing is a new event at the Youth Olympic Games, with both males and females aged 16–17 competing in bouldering, lead, and speed climbing. According to Smith et al. (Smith, Holmes, & McAllister, 2015), young athletes should be mindful of appropriately fueling for training to maintain energy availability for both performance and growth and growth should be tracked to ensure there is not an energy deficit. In a recent study, we assessed dietary intake patterns of competitive rock climbers, demonstrating that adolescents failed to meet target energy, CHO, and fat needs, but they did meet protein needs (Michael, Joubert, & Witard, 2019). In terms of training recommendations, future studies designed to track growth spurts and Tanner stages of puberty in adolescent rock climbers will be helpful to ensure proper training techniques are employed to prevent epiphyseal stress fractures. International bouldering competitions and finger specific strength training is discouraged for those under age 16, as those younger may be more susceptible to growth plate injury and have under-developed coordination and skills (Schöffl, Lutter, Woollings, & Schöffl, 2018).

Oxygen uptake for children (ages 10.9 ± 1.7 years) during climbing has been shown to be similar to adults (Watts & Ostrowski, 2014). Youth and adolescents may have inadequate anaerobic enzymes needed to support isometric holds and heavy loading of muscle tissue (Morrison & Schöffl, 2007). Adolescents may have decreased sweat rates, and thus hydration needs should be individualized and based on body mass rather than total volume (Smith et al., 2015).

Energy intake needs of young climbers vary based on age, sex, activity level, and growth periods. Adolescents aged 16–18 participating in heavy physical activity may require up to 2875–3925 kcal per day (Smith et al., 2015). In comparison, adolescent climbers may need to consume fewer kcals since rock climbing is generally not considered a high-intensity sport based on its physiological demands. Nonetheless, careful consideration of energy availability is crucial to support growth. Moreover, Smith, et al. (Smith et al., 2015) recommends 1.2–1.8 grams per kg protein for youth athletes and fat intakes of 25-30% of total kcal intake. Carbohydrate recommendations range from 3–8 grams per kg body weight or 30–60 grams per hour or exercise (Smith et al., 2015).

10. Practical application statement
In a sport such as rock climbing where errors could lead to injuries or fatality, nutrition and hydration are imperative. Nutrition for competitive rock climbing should include fueling adequately for the individual athlete. Nutritional recommendations for competitive rock climbers vary based on climbing discipline, body composition goals, climbing venue, and training phase. We recommend that dietary energy intakes of youth climbers, including children and adolescents, need to be adequate for fueling both athletic activities and growth. Preparation is essential for rock climbers, with fluids and food available at the venue to optimize physical and mental performance.
Competitive climbers such as those aiming for the Olympics should seek out the guidance of a nutrition professional to ensure proper fueling for performance, health, and injury prevention. Areas for further research are summarized in Table 3.

Acknowledgements
MM wrote and edited the manuscript. LJ and OW edited the manuscript.

Funding
There are no funding sources.

Author details
Marisa K. Michael1
E-mail: dietitian@realnutritionrdn.com
Oliver C. Wbard2
E-mail: oliver.wizard@stir.ac.uk
Lanae Joubert3
E-mail: ljoubert@nmu.edu
ORCID ID: http://orcid.org/0000-0002-0325-528X
1Health Sciences and Sport, University of Stirling, Stirling, Scotland.
2Physiology, Exercise and Nutrition Research Group, Faculty of Health Sciences and Sport, University of Stirling, Stirling, Scotland.
3Health and Human Performance, Northern Michigan University, Marquette, MI, USA.

Authorships
All authors approved the final version of this paper.

Conflicts of interest
The authors declare no conflict of interest.

Citation information
Cite this article as: Physiological demands and nutritional considerations for Olympic-style competitive rock climbing, Marisa K. Michael, Oliver C. Wizard & Lanae Joubert, Cogent Medicine (2019), 6: 1667199.

References
Arciero, P. J., Hannibal, N. S., 3rd, Nindl, B. C., Gentile, C. L., Hamed, J., & Vukovich, M. D. (2001). Comparison of creatine ingestion and resistance training on energy expenditure and limb blood flow. Metabolism, 51, 1429–1434. doi:10.1053/meta.2001.28159
Baker, L. B., Rollo, I., Stein, K. W., & Jeukendrup, A. E. (2015). Acute effects of carbohydrate supplementation on intermittent sports performance. Nutrients, 7, 5733–5763. doi:10.3390/nu7075249
Baláš, J., Panáčková, M., Strejcová, B., Martin, A., Cochrane, D. J., Kaláb, M., … Draper, N. (2014). The relationship between climbing ability and physiological responses to rock climbing. ScientificWorldJournal, 678387. doi:10.1155/2014/678387
Bertuzzi, R. C., Franchini, E., Kokubun, E., & Kiss, M. A. P. D. M. (2007). Energy system contributions in indoor rock climbing. European Journal of Applied Physiology, 101, 293–300. doi:10.1007/s00421-007-0501-0
Booth, J., Marino, F., Hill, C., & Gwinn, T. (1999). Energy cost of sport rock climbing in elite performers. British Journal of Sports Medicine, 33, 14–18. doi:10.1136/bjsm.33.3.14
Devries, M. C., & Phillips, S. M. (2015). Supplemental protein in support of muscle mass and health: Advantage whey. Journal of Food Science, 80, S1. doi:10.1111/1750-3841.12802
Dickson, T., Fryer, S., Blackwell, G., & Draper, N. (2012). Effect of style of ascent on the psychophysical demands of rock climbing in elite level climbers. Journal of Sports Technology, 5, 111–119. doi:10.1080/19346182.2012.686504

Table 3. Areas for further research

| Energy and macronutrient needs and expenditure | Dietary Supplements | Anthropometrics | Disordered eating patterns |
|-----------------------------------------------|---------------------|----------------|---------------------------|
| Adolescent climbers | Enhancing performance | Speed climbers | Prevalence in adolescents |
| Outdoor climbers | Alleviating “pump” | Modern lead climbers | Prevalence in recreational vs. competitive |
| Multi-day competitions | Promoting recovery | | Prevalence in males vs. females |
| Multi-day outdoor climbing expeditions | Buffers for lactate production | | Prevalence in each discipline |
| Boulders | Injury prevention/treatment | | |
| Lead climbers | Leucine | | |
| Speed climbers | Creatine | | |
| Belayers | Beta alanine | | |
| Injured climbers | Beet root juice | | |
| Training cycles | | | |
| Dietary intakes of competitive climbers in each discipline | | | |
| Assess climber nutrition knowledge | | | |

Michael et al., Cogent Medicine (2019), 6: 1667199
https://doi.org/10.1080/2331205X.2019.1667199
Draper, N., Jones, G. A., Fryer, S., Hodgson, C., & Blackwell, G. (2008). Effect of an on-site lead on the physiological and psychological responses to rock climbing. Journal of Sports Science & Medicine, 7, 692-698.

Espana-Romero, V., Jensen, R. L., Sanchez, X., Ostrowski, M. L., Szekely, J. E., & Watts, P. B. (2012). Physiological responses in rock climbing with repeated ascents over a 10-week period. European Journal of Applied Physiology, 112, 821-828. doi:10.1007/s00421-011-2022-0

Fogelholm, M. (2015). Micronutrients: Vitamins, minerals, and antioxidants. In Clinical sports nutrition (5th ed.) (pp.310–326). Sydney: Mc Graw-Hill Education.

Govus, A. D., Garvican-Lewis, L. A., Abbiss, C. R., Peeling, P., & Gore, C. J. (2015). Pre-altitude serum ferritin levels and daily oral iron supplement dose mediate iron parameter and hemoglobin mass responses to altitude exposure. PLoS ONE, 10(8), e0135120. doi:10.1371/journal.pone.0135120

Hamilton, B. (2011). Vitamin D and athletic performance: The potential role of muscle. Asian Journal of Sport Medicine, 2, 211–219. doi:10.5832/tasjsm.34736

Hollick, M. F., Binkley, N. C., Bischoff-Ferrari, H. A., Gordon, C. M., Hanley, D. A., Heaney, R. P., ... Weaver, C. M. (2011). Evaluation, treatment, and prevention of vitamin D deficiency: An Endocrine Society Clinical Practice Guideline. Journal of Clinical Endocrinology & Metabolism, 96. doi:10.1210/jc.2011-0385

IFSC World Championships. (2018, July 18). Key Figures. Retrieved from https://www.ifsc-climbing.org/index.php/world-competition/world-championships

Institute of Medicine. (2005). Dietary Reference Intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein, and amino acids.

International Federation of Sport Climbing: About the IFSC. (2019, August 7). About the IFSC. Retrieved from https://www.ifsc-climbing.org/index.php/9-about-ifsc/24-about-ifsc

IOC approves five new sports for Olympic Games Tokyo 2020. (2016, August 14). Retrieved from https://www.olympic.org/news/IOC-approves-five-new-sports-for-olympic-games-tokyo-2020

IOC Buenos Aires 2018 Youth Olympic Games: Proposal for Additional Sports. (2018, July 18). Retrieved online from https://stillmed.olympic.org/media/Document%20Library/OlympicOrg/Games/YouG/Summer-YOG/YOG-Buenos-Aires-2018-Youth-Olympic-Games/b2018-new-sports-Annex-1-Factsheets.pdf?go=2.63287211.520424737.1531853518-2019145073.1485288774

Jöger, R., Purpura, M., Shao, A., Inoue, T., & Kreider, R. (2011). Analysis of the efficacy, safety, and regulatory status of novel forms of creatine. Amino Acids, 40, 1369–1383. doi:10.1007/s00726-011-0874-6

Jeukendrup, A. (2014). A step towards personalized sports nutrition: Carbohydrate intake during exercise. Sports Medicine, 44, 25–33. doi:10.1007/s00729-014-0418-1

Joubert, L. J., Larson, A. J., & Weber, S. E. (2016, August 3). Nutrition and hydration strategies to enhance sport and multi-pitch climbing performance. Oral presentation presented at the 3rd Research Congress of the International Rock Climbing Research Association; Telluride, CO USA.

Jouris, K. B., McDaniel, J. L., & Weiss, E. P. (2011). The effect of Omega-3 fatty acid Supplementation on the inflammatory response to eccentric strength exercise. Journal of Sports Science & Medicine, 10, 432-438.

Kechikan, D. (2011). Optimizing nutrition for performance at altitude. Journal of Special Operations Medicine, 11, 12–17.

Lucas, J. (2016). Peaches Preaches: Confessions of a weigh-obsessed climber. Retrieved from https://www.climbing.com/people/peaches-preaches-confessions-of-a-weigh-obsessed-climber

Lutter, C., El-Sheikh, Y., Schöff, I., & Schöff, V. (2017). Sport climbing: Medical considerations for this new Olympic discipline. British Journal of Sports Medicine, 51, 2-3. doi:10.1136/bjsports-2016-096871

Macdonald, J. H., & Callender, N. (2008). Athletic profile of highly accomplished boulderers. Journal of Sports Science, 26, S131.

Maughan, R. J. (1999). Role of micronutrients in sport and physical activity. British Medical Bulletin, 55(s), 683-690. doi:10.1258/0007142991902556

Maughan, R. J., & Shirreffs, S. M. (2008). Development of individual hydration strategies for athletes. International Journal of Sport Nutrition and Exercise Metabolism, 18, 457–482.

Mermier, C. M., Janot, J. M., Parker, D. L., & Swan, J. G. (2000). Physiological and anthropometric determinants of climbing performance. British Journal of Sports Medicine, 34, 359–366. doi:10.1136/bjsm.34.5.359

Mermier, C. M., Robergs, R. A., McMinn, S. M., & Heyward, V. H. (1997). Energy expenditure and physiological responses during indoor rock climbing. British Journal of Sports Medicine, 31, 224–228. doi:10.1136/bjsm.31.3.224

Michael, M., Joubert, L., & Wiltard, O. (2019). Assessment of dietary intake and eating attitudes in recreational and competitive adolescent rock climbers: A pilot study. Frontiers in Nutrition, 6, 64. doi:10.3389/fnut.2019.00064

Mladenov, L., Michailov, M., & Schöff, I. (2001). Anthropometric and strength characteristics of world-class boulderers. Medicina Sportiva, 4, 231–238.

Moore, D., Slater, G., & Phillips, S. (2015). Protein. In L. Burke & V. Deakin (Eds.), Clinical sports nutrition: Carbohydrate intake during exercise. Sports Medicine, 24, 852-861. doi:10.1136/bjsports-2014-093502

Mountjoy, M., Sundgot-Borgen, J., Burke, L., Carter, S., Constantini, N., Lebrun, C., ... Ljungqvist, A. (2014). The IOC consensus statement: Beyond the female athlete triad—Relative energy deficiency in sports (RED-S). British Journal of Sports Medicine, 48, 491–497. doi:10.1136/bjsports-2014-093502

Rowson, E. S., Miles, M. P., & Larson-Meyer, D. E. (2018). Dietary supplements for health, adaptation, and recovery in athletes. International Journal of Sport Nutrition and Exercise Metabolism, 28, 188–199. doi:10.1123/ijsnem.2017-0340

Schöff, V., Lutter, C., Woolings, K., & Schöff, I. (2018). Pediatric and adolescent injury in rock climbing. Research in Sports Medicine, 26(sup1). 91–113. doi:10.1080/15438627.2018.1438278

Sheel, A. W. (2004). Physiology of sport rock climbing. British Journal of Sports Medicine, 38, 355–359. doi:10.1136/bjsm.2003.008169

Silva, T., de Souza, M. E. D. C. A., de Amorim, J. D., Stathis, C. G., Leandro, C. G., & Lima-Silva, A. E. (2014). Can carbohydrate mouth rinse improve performance during exercise? A systematic review. Nutrients, 6, 1–10. doi:10.3390/nu6010001
Smith, E. J., Storey, R., & Ranchordas, M. K. (2017). Nutritional considerations for bouldering. *International Journal of Sports Nutrition and Exercise Metabolism, 27*(4), 314–324. doi:10.1123/ijsnem.2017-0043

Smith, J. E., Holmes, M. E., & McAllister, M. J. (2015). Nutritional considerations for performance in young athletes. *J Sport Med, 2015*, 734649. doi:10.1155/2015/734649

Sousa, M., Teixeirea, V., & Soares, J. (2014). Dietary strategies to recover from exercise-induced muscle damage. *International Journal of Food Science and Nutrition, 65*, 151–163. doi:10.3109/09637486.2013.849662

Spriet, L. L. (2014). Exercise and sport performance with low doses of caffeine. *Sports Medicine, 44*, 175–184. doi:10.1007/s40279-014-0257-8

Stokes, T., Hector, A. J., Morton, R. W., McGlory, C., & Phillips, S. M. (2018). Recent perspectives regarding the role of dietary protein for the promotion of muscle hypertrophy with resistance exercise training. *Nutrients, 10*(180). doi:10.3390/nu10020180

Watts, P. B., Daggett, M., Gallagher, P., & Wilkins, B. (2000). Metabolic response during sport rock climbing and the effects of active versus passive recovery. *International Journal of Sports Medicine, 21*, 185–190. doi:10.1055/s-2000-302

Watts, P. B., España-Romero, V., Ostrowski, M. L., & Jensen, R. L. (2019). Change in geometric entropy with repeated ascents in rock climbing. *Sports Biomechanics*. doi:10.1080/14763161.2019.1635636

Watts, P. B., Joubert, L. M., Lish, A. K., Mast, J. D., & Wilkins, B. (2003). Anthropometry of young competitive sport rock climbers. *British Journal of Sports Medicine, 37*, 420–424. doi:10.1136/bjsm.37.5.420

Watts, P. B., Martin, D. T., & Durtchi, S. (1993). Anthropometric profiles of elite male and female competitive sport rock climbers. *Journal of Sport Sciences, 11*, 113–117. doi:10.1080/02640419308729974

Watts, P. B., & Ostrowski, M. L. (2014). Oxygen uptake and energy expenditure for children during rock climbing activity. *Pediatric Exercise Science, 26*, 49–55. doi:10.1123/pes.2-13-0035

Witard, O. C., Jackman, S. R., Breen, L., Smith, K., Selby, A., & Tipton, K. D. (2013). Myofibrillar muscle protein synthesis rates subsequent to a meal in response to increasing doses of whey protein at rest and after resistance exercise. *American Journal of Clinical Nutrition, 99*(1), 86–95. doi:10.3945/ajcn.112.055517

Woolf, K., & Manore, M. M. (2006). B-vitamins and exercise: Does exercise alter requirements? *International Journal of Sports Nutrition and Exercise Metabolism, 16*, 453–484. doi:10.1123/ijsnem.16.5.453

Zapf, J., Fichtl, B., Wielgoss, S., & Schmidt, W. (2001). Macronutrient intake and eating habits of elite rock climbers. *Medicine & Science in Sports & Exercise, 33*, 572. doi:10.1097/00005768-200105001-000407
