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Strength Training for Long-Distance Triathletes: Theory to Practice

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ABSTRACT

Concurrent training, commonly acknowledged as a training method where strength and endurance training are completed complementary to each other, is a strategy often implemented in endurance cyclists' and runners' programs to improve physiological determinants of success such as exercise economy. Although concurrent training methods and strategies have been examined to a large extent in endurance cyclists and runners, literature examining optimal concurrent training methods to improve physiological variables in long-distance triathletes is minimal, leaving optimal programming relatively unknown. This practical applications paper identifies and outlines current concepts and considerations regarding concurrent training for long-distance triathletes including mechanisms contributing to improved performance, muscle and movement patterns used, exercise selection, load, velocity of movement, scheduling, frequency, and duration of training. Common misconceptions related to concurrent training are also identified and practical considerations for the application of concurrent training for coaches, athletes, and other professionals to improve all 3 disciplines of triathlon are discussed.

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INTRODUCTION

Despite a large body of research recommending the implementation of concurrent strength and endurance training for optimal performance and physiological improvements, coaches tend to have opposing views on the implementation of strength training (ST) in endurance athletes' programs. The inclusion of ST into long-distance (LD) triathletes' programs can improve both cycling economy (CE) and running economy (RE) which is considered critical for success in LD triathlon (58,62). Furthermore, research has demonstrated that ST can significantly improve performance variables (economy, time-trial performance, reduced heart rate [HR] at submaximal intensities, velocity at $\dot{V}O_2$max [$v\dot{V}O_2$max], and power at $\dot{V}O_2$max [$w\dot{V}O_2$max]) in single mode endurance sports such as cycling and running (10,11,25,61,71,72,79,80,83,90,91,98,100). Long-distance triathlon is classified as any triathlon distance greater than an Olympic distance race (>1,500-m swim, 40-km cycle, and 10-km run) (59) with the 2 most common forms known as a half-iron distance (1.9-km swim, 90-km cycle, and 21.1-km run) and full iron-distance (3.8-km swim, 180-km cycle, and 42.2-km run) distance races.

A recent study examining characteristics of ST habits in LD triathletes found that only 54.6% of triathletes included a form of ST in their normal training regime with participants reporting time restraints and a lack of knowledge regarding what strength exercises to complete, how to progress exercises, and technique as the primary barriers (59). As ST is considered a broad term that encompasses many different variables that can be manipulated (51), it can be complex for a coach or athlete to understand the optimal ST prescription to achieve the athlete's goals. Variables that can be manipulated include type of muscle contraction (isometric, concentric or eccentric), exercise selection (open or closed chain), volume (number of repetitions, sets, load lifted), velocity of movement, rest intervals, and

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frequency of training (52). In addition, the periodization of a training program will provide the overall structure and the specific training stimulus and subsequently will determine the adaptation and response of the individual. The complexity of understanding optimal ST prescription for LD triathletes is highlighted in a recent study by the current authors displaying significant improvements in CE after 12 weeks of moderate load ST with no effect on RE or swim time (58). However, a subsequent 12-week heavy load ST program significantly improved RE, but did not further improve CE or swim time (58). Specific to endurance training, coaches may prescribe "strength-endurance" sessions such as swimming with paddles, cycling in a big gear, or running up a hill to improve strength. During these "strength-endurance" sessions, an athlete will complete hundreds or even thousands of repetitions for each of these movements (i.e., if a runner runs up a hill at a cadence of 170 steps per minute for 2 minutes, they will complete 340 repetitions and they may repeat this multiple times in a session). These "strength" parameters do not conform with more traditional ST prescription (51) and therefore do not encompass ST, despite the coach implementing these sessions with the goal of "improving strength."

Although there are numerous studies supporting the implementation of ST to improve performance and physiological variables in endurance athletes (10,11,25,61,71,72,79,80,83,90,91,98,100), practical application papers primarily focus on running (8), single-mode sports (9), or are outdated (20). Therefore, the purpose of this paper is to educate coaches and athletes on the benefits of completing concurrent strength and endurance training to improve physiological factors contributing to LD triathlon performance. Special consideration is given to the varying muscle groups and muscle contractions used during the 3 disciplines of triathlon when compared with single-mode endurance sports. This paper aims to address the reported barriers of a lack of knowledge regarding ST implementation so coaches and athletes can be confident when implementing ST into their current training regime and in turn improve performance. In addition, this paper outlines the differences in ST programming for the 3 disciplines of triathlon and identifies additional factors to consider when implementing ST, such as suboptimization of endurance performance, and scheduling of ST.

PHYSIOLOGICAL VARIABLES CONTRIBUTING TO PERFORMANCE IN LONG-DISTANCE TRIATHLETES

EXERCISE ECONOMY

Exercise economy is defined as the energy demand required at a given absolute submaximal intensity and is often referred to as one of the key indicators of performance in endurance athletes (7). A triathlon consists of swimming, cycling, and running performed consecutively for long durations, where extreme energy demands are placed on the body, especially at the critical end stages of the race when energy reserves are depleted (43,63,64). The cycle and run comprise the longest disciplines within a LD triathlon race and account for 55 and 35% of the total race time respectively (33), emphasizing their importance for overall performance. It is acknowledged that CE and RE are crucial for success in LD triathlon and to improve performance in these disciplines, athletes must train their body to use their energy supplies more efficiently (43,63,64). Cycling and RE are multifactorial and are influenced by anthropometric, physiological, biomechanical, and neuromuscular factors (82). The efficiency of neuromuscular performance can be affected by muscle fiber type, neural signaling, motor programming, force production, and musculotendinous stiffness (7). These factors can be modified through implementing various training strategies, with ST being recognized as one of the most effective interventions for improving RE (82,83).

MAXIMAL OXYGEN UPTAKE AND LACTATE THRESHOLD

High levels of aerobic power are crucial for success in LD triathlon, with high-performing triathletes achieving maximal oxygen uptake ($\dot{V}O_2max$) values nearly twice the value of an untrained individual (13). Many high-performing endurance athletes have similar and comparable high $\dot{V}O_2max$ values, although RE can vary largely among individuals, and thus can be the factor that separates the top athletes from novices (23,65). In fact, up to 65% of variation in race performance in high-level runners could be attributed to differences in RE with athletes having the greatest RE outperforming their competition (23). Lactate threshold, defined as the workload beyond which there is a rapid accumulation of blood lactate (BLa) is also highly correlated to triathlon performance (92). The LT identifies the fraction of $\dot{V}O_2max$ that can be sustained for a prolonged effort during an endurance event such as a LD triathlon (92). Therefore, athletes with higher LT values can maintain a higher submaximal intensity without a continuous rise in BLa, which is associated with a rapid increase in anaerobic metabolism contributing to the energy cost (E_C) of movement.

INJURY PREVENTION

Injuries are a common occurrence among LD triathletes and may be associated with the substantial training volumes undertaken (13.5–21.5 hours per week) (37,101) by athletes. Anderson et al. examined injury occurrence in LD triathletes over a 26-week training period with 87% of the entire cohort reporting a form of overuse injury, and over half of these injuries being classified as a "substantial" problem (defined as "those leading to moderate or severe reductions in training volume, or moderate to severe reductions in sports performance, or complete inability to participate in sport") (2). Throughout the 26-week period, more than half of the cohort was suffering from an overuse injury that involved the knee, lower leg, lower back, or shoulder (2). As training is one of the most important modifiers of endurance performance (48) and LD triathletes generally complete high training volumes, it may be hypothesized that more time spent away from training due to injury can result in decreased performance. Sustaining an injury from training or racing can result in athletes missing or altering training sessions, thereby increasing the time taken to reach a higher level of performance in a competition. Conversely, if a triathlete avoided injury and could maintain a higher volume of training, which seems necessary for performance in LD triathlon, they may achieve an optimal level of performance for their event. A recent meta-analysis showed that ST implementation was the most effective injury prevention protocol as ST reduced overuse sporting injuries by almost half (54). Therefore, it may be hypothesized that the inclusion of ST may benefit LD triathlete performance through the reduction of injury occurrence.

Research in LD triathletes has indicated that the ankle and knee are the most common injury sites. Approximately 77.7% of reported overuse injuries affect the Achilles tendon and 66.6% affect the knee (30). Vleck et al., also observed that the most frequent injury sites incurred by LD triathletes were the knee (44%), calf (20%), hamstring (20%), and lower back (20%) with most overuse injuries sustained from running (60%), whereas cycling accounted for 32% and swimming 16% of overuse injuries.

MUSCLE GROUPS AND MOVEMENT PATTERNS USED IN TRIATHLON

RUNNING

During running, a ground reaction force between 2–3 times the individual's body weight is taken through the athlete's single lower limb with every step. This force is counteracted by the spring-like behavior of the supporting leg's musculotendinous system (69,82). Mechanical energy is stored in the muscles and tendons during the contact phase of running before being expended during the push off phase (34). The recovery and expenditure of this stored energy reduces the need for muscular contractions, therefore decreasing energy requirements (34). This spring-like behavior of the lower limbs and the use of elastic energy emphasizes the importance of musculotendinous stiffness for optimal running performance and economy, with estimates on oxygen consumption during running being 30–40% higher without the contributions from elastic energy storage and return (21). The strength of the triceps surae muscles (gastrocnemius and soleus) is associated with RE as these muscles account for up to 40% of the total metabolic cost of running in recreational athletes and 25% in high level athletes (36). The triceps surae are the greatest contributors of forward propulsion during running with their common tendon of insertion (Achilles tendon) efficiently returning 90% of mechanical energy during push off with the tendon forces estimated to be 6–8 times the athlete's body weight (70). Of the triceps surae muscle group, the soleus is the primary contributor to propelling the body forward (41). As running speeds increase, the soleus muscle fibers contract with the highest velocities of any muscles during late stance phase, allowing quicker plantarflexion and therefore decreased ground contact time which is associated with running speed and subsequently economy (29,40).

The hamstrings, quadriceps, and tibialis anterior also play large contributing roles during running, contracting both concentrically and eccentrically during different phases of the running gait, thus working together to increase musculotendinous stiffness and enhancing force production in the braking and/or propulsive phases of running (53). The gluteus maximus has an important role to produce hip extension and works predominantly concentrically during running. The upper limbs do not contribute markedly to running because they generate less than 1% of running acceleration (41). It is important to note, however, that the arms can effectively counterbalance momentum of the lower limbs and may influence lower-limb muscle activity, especially that of the gluteus maximus via the posterior oblique swing (where the latissimus dorsi and gluteus maximus muscle link posterior to the spine by the thoracolumbar fascia) (85).

CYCLING

In contrast to running, only concentric muscle contractions occur during road cycling (16,31), thus decreasing the ability of cyclists to store energy during eccentric muscle contractions and utilize it in the same manner as runners. The quadriceps, gluteal muscles, biceps femoris, and tibialis anterior work synergistically to generate power during the first quarter of the pedal stroke (top of the pedal stroke to 90°) (75,76,87). The quadriceps then become less active, whereas the hamstrings, gastrocnemius, and gluteus maximus become more active until the bottom dead center of the pedal stroke to complete the propulsive phase of cycling (75,76,87). The hip flexors (iliacus, psoas, and short head of biceps femoris) are also active during cycling, enabling the effective movement upward of the pedal following the downward propulsive stroke (75,76). The ankle joint is stabilized during the whole pedal stroke to ensure force is transferred through the ankle into the crank, which is done by co-activation of the ankle plantar flexors (triceps surae) and the tibialis anterior (46,75,76).

Similar to running, the muscles in the trunk and arms provide a counterbalance force to the lower limbs during pedaling with the hand, arm, shoulder, abdomen, and back forming a muscular sling that moves back and forth in support of the trunk and pelvis (87). It should be noted that in LD triathlon racing, athletes primarily use time-trial bikes where the position is predominantly focused on improving aerodynamics when compared with a road bike. Such changes in bike type and position can result in some changes in muscle activation. A more aerodynamic position on a time-trial bike can result in a higher degree of hip flexion, which can decrease activation of the hip flexors (17,50). To compensate for the loss in hip flexor strength, it is proposed that the knee flexors (hamstrings) increase activity in the time-trial position. An increase in hamstring activity in cyclists has been associated with an increase in force production during the pedal stroke (17,50).

SWIMMING

The main propulsive muscles used in front crawl swimming are the pectoralis major and latissimus dorsi; however, studies show a high variation in muscle activation, reflecting the high variability in swim stroke technique among athletes (73,86). An important characteristic for success during front crawl swimming is stabilizing the upper limb allowing stronger propulsion underwater during the swim stroke. The pectoralis major, teres minor, and rotator cuff muscles work together during the swim stroke in a stabilizing manner (73,86). The leg kick during swimming is suggested to be used to stabilize the body, allowing better kinematics of the arm stroke, rather than as a propulsive force. This is because of research suggesting that the kick only contributes to 10% of propulsion during front crawl swimming (73,86). During open water (OW) swimming, the kinematics of the swim stroke will vary from pool swimming because of the water conditions (swell, water temperature, waves, tides) and wearing of wetsuits, which can influence efficiency, technique, and stroke mechanics. Furthermore, in OW swimming, an emphasis is placed on making the swim stroke movement as efficient as possible, rather than focusing on power output (5).

CONCURRENT STRENGTH AND ENDURANCE TRAINING IN LONG-DISTANCE TRIATHLETES

ST programs demonstrating significant physiological and performance improvements in endurance sports are generally comprised of high load and low repetition exercises, commonly referred to as "heavy" or "maximal" ST (1–8 repetitions, 3–5 sets, ≥80% of 1 repetition maximum [1RM]). This may be contrary to popular processes used by some endurance coaches who may implement low load and high repetition programs to focus on muscular endurance, because they believe this will better suit the metabolic and muscular demands of the endurance athlete. It is important for coaches to understand that traditional endurance training (e.g., long duration aerobic focused cycles or running specific interval training) should be prescribed to address the cardiovascular and muscular endurance aspects of performance, whereas recent research suggests ST should be implemented to focus on improving maximal strength, dynamic rate of force development (RFD), muscular power, and improved neural activity (12,18,81,90,91).

Studies examining the efficacy of concurrent training have shown varying results, predominantly because of the differences in ST protocols and methodology completed. A 26-week progressive load ST program has been shown to significantly improve both CE ($p = 0.001$, 7.53%, ES = 0.97) and RE ($p = 0.004$, 4.86%, ES = −0.57) in the endurance-strength group, with no significant changes demonstrated in the control group (58). This intervention was comprised of two 12-weeks ST blocks with the first consisting of "moderate" load ST (3–4 sets, 8–12 repetitions, ≤75% of 1RM), which was then followed by a 12-week "heavy" load ST program (3–5 sets, 1–6 repetitions, ≥85% of 1RM). The significant improvements in RE were only seen during the final 12-week heavy ST block, whereas significant improvements in CE were seen after the initial 12-week moderate load ST block. Running and CE was tested during a simulated LD triathlon, replicating the specific competition and physiological demands of LD triathlon while accommodating for accumulative fatigue from the previous discipline (60). In addition, the improvements seen in RE were greater than both the TE and smallest worthwhile change associated with measuring RE (82), therefore potentially demonstrating meaningful physiological improvements. Another study examining concurrent ST in 15 well-trained triathletes saw significant improvements in RE and maximal strength measures ($p < 0.05$) in the endurance-strength group only after the completion of a 14-week heavy load ST program (3–5 sets of 3–5 repetitions to failure) (62).

In an additional study examining 14 well-trained triathletes, participants completed a 5-week heavy load ST program (3–5 sets, 3–5 repetitions to failure, ≥90% of 1RM) that resulted in significant improvements in maximal strength (6%) in the endurance-strength group with no associated change in body mass (42). The endurance-strength group also showed an increase in electromyography activity in the vastus lateralis, allowing the authors to conclude the increase in maximal strength most likely resulted from neural mechanisms such as increased neural activation, more efficient motor unit synchronization, more efficient excitability of the α-motor neurons, and decreased Golgi tendon organ inhibition (42). The significant improvement in maximal strength (6%), was smaller than that of other similar studies in endurance cyclists and runners that have shown improvements in maximal strength measures between 14–45% (10,62,77,79,90,91,100). The relatively smaller improvements in maximal strength and EMG activity seen by Hausswirth et al. did not translate to improvements in CE, therefore suggesting that 5 weeks of heavy ST may not be a sufficient training duration to elicit significant CE changes.

The effectiveness of plyometric ST protocols in triathletes has also been assessed by Bonacci et al., where 3 × 30-minute plyometric sessions per week were performed for 8 weeks in 8 moderately trained triathletes, with EMG activity showing changes in muscle recruitment patterns more closely replicating an isolated run. However, these favorable neuromotor outcomes did not translate to significant improvements in RE (19).

Similar findings are also seen in the literature examining concurrent ST in duathletes (bike, run) and cyclists with participants significantly improving CE after 8–12 weeks of heavy ST completed twice per week (10,79,91,98,100). In 2 of these studies, decreases in oxygen consumption and HR are not seen until the later stages of prolonged submaximal testing periods (79,100), emphasizing the importance of ST to improve CE when athletes become fatigued after prolonged periods. In addition, participants in the endurance-strength groups of these studies significantly improved performance during a 5-minute all-out cycle after a prolonged submaximal exercise (3 hours), which can replicate a sprint or increased effort to finish at the end of a LD triathlon race (79,100). The authors proposed that the reduced oxygen consumption and HR during the prolonged submaximal work reduced physiological strain, fatigue, and energy consumption, which then allowed the athletes to better conserve glycogen stores for the all-out 5-minute effort (79,100). Furthermore, a 16-week maximal ST program completed by elite cyclists resulted in a significant improvement in power during a 45-minute cycling time-trial (8%) in the endurance-strength group, whereas the control group did not significantly improve time-trial performance (1). Total distance covered, total work, and average power production were significantly greater in the endurance-strength group than the control group post-training (1). Similar results are seen in female duathletes with a significant improvement in mean power during a 40-minute all-out time trial (98). In addition, Ronnestad et al. found significant improvements in $w\dot{V}O_2max$ after the completion of maximal ST in cyclists ($p < 0.05$; ES = 0.81 (78), ES = 0.84 (79)).

Studies implementing ST protocols in endurance runners have also shown similar results with a recent systematic review including LD runners, duathletes, and triathletes seeing improvements in RE between 2–8% (ES 0.14–3.22) after the completion of heavy ST programs (>80% of 1RM) (18). In addition, significant improvements in RE have been seen from a plyometric/explosive-based ST program (83) or a "combination" program (including both plyometric and heavy strength exercises) (10). Significant improvements in 3000-m–5000-m time-trials and $v\dot{V}O_2max$ have also been seen as the result of plyometric/explosive ST-based programs in runners (14,61,71,88).

To the best of our knowledge, there is no research examining concurrent strength and endurance training on OW swimming performance measures; however, the literature recommends the inclusion of ST in OW swimmers' normal training regime (97). A study examining training loads of elite swimmers identified that LD swimmers typically included dry-land ST as a consistent part of their training regime (74). These ST programs seem to focus on both metabolic conditioning and maximal strength (74). Dry-land ST programs for shorter distance pool swimming have shown significant improvements in swimming performance with the prescription of heavy ST programs (2–3 repetitions, 3–5 sets at 80–90% of 1RM) (4,38); however, caution should be taken when using these results as the ST protocols may have improved starts and turns in pool swimming which may not be applicable for OW swimming.

MECHANISMS CONTRIBUTING TO PHYSIOLOGICAL IMPROVEMENTS

Various neurological and morphological adaptations have been proposed to contribute to improvements obtained from concurrent strength and endurance training. Improvements in musculotendinous stiffness are commonly cited as one of the most important adaptions from ST programs to improve endurance performance, especially in running (62,83,90). Increased musculotendinous stiffness can improve the use of elastic energy from the tendons and therefore decrease the muscle contraction required during running, reducing the demands for energy in the muscles and therefore improve the E of running (11).

Another proposed mechanism is the significant improvements in dynamic RFD from increased neural activation of muscle fibers. This would enable the athlete to rapidly push off the ground or through the pedal, decreasing contraction time and the constriction of blood flow and enable increased blood to flow to the working muscles, therefore facilitating an increase in oxygenation and substrate use (90,91).

ST may also result in an increase in the contribution of work from the type I muscle fibers and delay the recruitment of the type II fibers (24,45). Furthermore, ST may also increase the proportion of the less fatigable type IIa muscle fibers at the expense of a reduction in the type IIx fibers which may further contribute to performance improvements in endurance athletes (1).

BARRIERS AND MISCONCEPTIONS ABOUT STRENGTH TRAINING IN LONG-DISTANCE TRIATHLETES

Although there is a large body of research supporting the implementation of ST for performance optimization in endurance athletes, LD triathletes still perceive some barriers around the completion of ST (59). Although a concern of hypertrophy may initially be considered as a forefront barrier, only 5.1% of LD triathletes reported this as an ST barrier (59). Studies implementing heavy ST in endurance athletes' programs have frequently shown no changes in body mass in triathletes, cyclists, and runners (62,90,91). Endurance exercise may negatively affect intracellular pathways important for myofibrillar protein synthesis, therefore inhibiting muscle hypertrophy, which may contribute to the lack of muscle hypertrophy and body mass reported in concurrent strength and endurance training studies (22). However, contrary to this, some studies investigating concurrent strength and endurance training have reported a significant increase in muscle cross sectional area (CSA) post-ST interventions in both runners and cyclists, with no associated increase in body mass (77,98,99). Therefore, it is possible that as a result of ST, some fat mass may be replaced by muscle mass with no overall change in body mass (77). A relationship between quadriceps muscle CSA and improved CE ($r = -0.54$) has been demonstrated (98), indicating the potential importance of a small increase in muscle CSA for improved performance. Therefore, an increase in muscle size should not be a barrier inhibiting triathletes from completing concurrent strength and endurance training.

Time restraints are the primary perceived barrier reported by LD triathletes (53.1%), which may be because of the large volumes of endurance training currently undertaken by LD triathletes (59). Implemented ST programs that have resulted in improvements in RE and CE are relatively short in duration (30–60 minutes), especially when compared with a key endurance training session involving an endurance cycle or run. Control groups in most concurrent strength and endurance training studies did not significantly improve endurance performance; therefore it could be hypothesized that the inclusion of ST, at the cost of an endurance training session may improve performance whilst also being more time effective than working on endurance training alone (10,11,61,71,72,79,80,83,90,91,98,100). Another prominent barrier contributing to the lack of ST in LD triathletes was that athletes were not confident on what exercises to complete, technique, and how to progress exercises with 52.5% of athletes reporting this as a barrier, emphasizing the need to educate athletes and also coaches regarding appropriate and optimal ST programming (59).

STRENGTH TRAINING PROGRAMMING FOR LONG-DISTANCE TRIATHLETES

EXERCISE SELECTION

For optimal performance in endurance sports, the hip, knee, and ankle musculotendinous systems need to work simultaneously to produce force against the ground or pedal (11,12). Multi-joint, closed kinetic chain (where the distal limb is fixed) compound exercises should be included in ST programs because these generally result in greater performance enhancements when compared with single-joint, isolated exercises (89). In addition, because time restraints are the largest reported barrier by triathletes preventing the completion of ST (59), compound exercises are time effective and can focus on multiple muscle groups and movements at once. When selecting strength exercises, the coach must consider the training transfer effect of each exercise into a performance adaptation.

Exercises selected should closely replicate similar movement patterns and use the same muscle groups as those used in the sport to allow a greater transfer to overall performance. Using the same muscle groups and replicating actions used, the athlete will facilitate neural and structural adaptations of specific and appropriate muscle groups (81). However, this task is complicated in triathlon because of the nature of the varying muscle groups and movement patterns used in the 3 different disciplines as outlined above. Furthermore, the swim and cycle disciplines do not involve a ground reaction force and therefore do not use the storage of elastic energy, therefore suggesting that different muscular contractions will take place for each discipline.

The most common exercises used in concurrent strength and endurance training literature for cyclists and runners include; a back squat and/or leg press (1,10,11,25,62,72,77,80,84,90,91,98,100), deadlift variations or hamstring curls (1,10,11,62,84), ankle plantarflexion based movements (1,25,32,62,79,80,84, 98–100), and a hip flexion or lunge variations (10,11,72,79,80,98–100). Only a small number of studies examining concurrent strength and endurance training included upper body or "trunk" exercises (32,49,72). It should be noted that compound exercises such as deadlifts and back squats can also substantially load the upper body and trunk muscles while strengthening the lower limbs.

The implementation of deadlift variations is more scarce in literature when compared with squat variations; however, the programming of deadlift variations is encouraged for both injury prevention and strength and power development of the posterior chain muscles (8). There should be an emphasis on the inclusion of squats for cycling performance, with one study showing significant improvements in CE and time to exhaustion in the endurance-strength group from incorporating only back squats in a ST program (91).

A form of bent-knee ankle plantarflexion exercise that targets tricep surae muscles, particularly the soleus such as a single leg (SL) seated calf raise should always be included. This is because of runners who possess the highest RE values presenting with greater strength of the triceps surae muscles and greater tendon-aponeurosis stiffness (3,34,35). To strengthen the triceps surae muscles appropriately for improving RE, an emphasis should be placed on having a bent knee. Of the triceps surae muscle group, the soleus is the primary contributor to propelling the body forward (41) and as running speeds increase, the soleus muscle fibers contract with the highest velocities of any muscles during late stance phase, which is associated with running speed and subsequently economy (29,40). As the soleus crosses only the ankle joint, a bent-knee plantarflexion movement will target the soleus more than a straight-legged movement which will target the gastrocnemius which crosses both the knee and ankle joint.

Although the use of a power or hang clean is not commonly incorporated in concurrent strength and endurance training literature, 2 recent practical review papers have recommended the inclusion of these exercises because they focus on posterior chain muscles that are used during endurance events and have a strong training transfer effect (8,9). Furthermore, a power or hang clean can improve hip extension RFD while also improving upper body strength (8,9). If the athlete finds the power or hang clean movement too complex, this may be regressed to a triple extension movement through the lower limbs and an emphasis must be placed on managing the load appropriately.

As well as traditional heavy ST, plyometric and explosive-based training can be effective in improving RE with common popular plyometric exercises including CMJ, jump squats, hurdle jumps, hopping, pogos, and drop jumps (14,71,83,88). Seven studies have compared performance outcomes of heavy ST to plyometric/explosive training (6,14,39,84,93,94) in endurance runners with 4 of these (6,39,93,94) showing greater improvements in RE from heavier load ST over plyometric protocols, suggesting heavy ST programming may be more beneficial for improving RE. Interestingly, plyometric and lighter load ST protocols seem to have no impact on CE in endurance cyclists (19,55). Plyometric training may not improve CE as only concentric muscle contractions occur during the pedal stroke, thus eliminating the need for storage and return of elastic energy (16,31).

To the best of our knowledge, there have been no studies investigating the efficacy of ST programs to prevent injuries in LD triathletes; however, ST programs have been shown to reduce overuse sporting injuries by almost half in a variety of other sports (54). The implementation of ST has however been recommended for masters (≥40 years old) and female triathletes to decrease injury risk (57). To assist in preventing the high occurrence of injury in LD triathletes, ST programs should consider including some specific injury prevention exercises. Considering that injuries affecting the knee, calf, Achilles, shoulder, and lower back are consistently recognized as areas at risk of high injury occurrence in LD triathletes (30,101), some exercises could be implemented to specifically address these areas.

In addition, ST can be incorporated to help improve biomechanics and absorption of ground reaction forces to help decrease the high occurrence of stress fractures in triathletes (57,68). These injury prevention-based exercises may be included as an "activation" or "assistance" exercise which can be completed before heavy ST and act as a dynamic warm-up. Both hip and knee strengthening programs can be effective in minimizing patellofemoral pain in a variety of participants, including runners (95). There is a positive bias toward addressing hip abductor and

Table 1
Selection of strength exercises and associated triathlon discipline specifically targeted

Exercise	Swimming	Cycling	Running
Injury prevention			
Wall slide, SL deadlifts, step-up/step-downs, pelvic drops, hip abduction		x	x
Scapula push-ups, shoulder internal/external rotation, seated row	x		
Explosive/plyometric			
Pogo jump, depth jump, countermovement jump			x
Heavy strength			
Half range or 90° squat		x	x
Deadlift	x	x	x
SL leg press		x	x
Seated SL calf raise	x	x	x
Lat pull-down	x	x	x
Standing hip flexion on cable machine		x	x
Lunge/split squat		x	x
Glute hamstring raise		x	x
Power clean/hang clean	x	x	x
Bent-over row	x	x	x
Weighted hip thrust		x	x

90° = knee angle to 90°; half range = femur parallel to ground; SL = single leg.

Table 2
Example strength training session addressing all disciplines for long-distance triathletes

Exercise	Sets	Repetitions	Loads
Injury prevention			
Scapula push-ups	3	12	Bodyweight
Wall slides	3	6 each leg	Bodyweight
Pelvic drops	3	12 each leg	Bodyweight
Performance/strength[a]			
Deadlift	3	6	85% of 1RM
Back squat	3	6	85% of 1RM
Single leg seated calf raise	3	6	85% of 1RM
Lat pull-down	3	6	85% of 1RM

[a]All performance/strength exercises completed with a 3-second eccentric lower, as fast as possible concentric phase. If the athlete is new to strength training or accumulating excessive fatigue, decrease the number of performance heavy strength exercises as appropriate.

external rotator strengthening exercises for optimal results in reducing knee pain with exercises such as wall slides, SL deadlifts, pelvic drops, and step-ups and step-downs being implemented in strengthening programs (95). The implementation of hip strengthening exercises, also known as "assistance" exercises can improve running mechanics and have been prescribed concurrently with heavy ST, resulting in significant improvements in RE and $\dot{V}O_2$max (11). To address both Achilles and calf injuries, strengthening of the triceps surae and loading the Achilles through an ST may be effective in decreasing pain and improving function (67).

To address all of the above factors while also taking into consideration the time restraints reported by LD triathletes, ST programs should predominantly include heavy (1–8 repetitions, 3–5 sets, ≥80% of 1RM) exercises to address all 3 disciplines. If improvements in RE are the primary focus, 1–2 explosive exercises may also be included. The inclusion of some accessory work as a form of dynamic warm-up or activation to prevent injuries and therefore potentially improve performance in LD triathletes is also recommended. Table 1 outlines ST exercises commonly used and recommended in literature and the associated triathlon discipline targeted with each exercise. Tables 2–5 outline example ST sessions that can be included in LD triathletes' programs and sessions targeting specific triathlon disciplines.

Table 3
Example strength training session with a swim focus for long distance triathletes

Exercise	Sets	Repetitions	Loads
Injury prevention			
Scapula push-ups	3	12	Bodyweight
Shoulder internal/external rotation	3	12	Moderate resistance
Performance/strength[a]			
Hang clean	3	6	85% of 1RM
Lat pull-down	3	6	85% of 1RM
Bent-over row	3	6	85% of 1RM

[a]All performance/strength exercises completed with a 3-second eccentric lower, as fast as possible concentric phase with the exception of the hang clean which should be completed with the concentric phase as fast as possible and the athlete taking time between each repetition to ensure good technique.

LOAD, VELOCITY, AND REST

Research examining concurrent strength and endurance training show the largest performance improvements are generated primarily from moderate-to-progressively heavy load ST exercises (≥80% of 1RM) with 2–3 minutes of rest between each set (10,11,39,62,71,72,77–79,83,84,88,90,91, 96,99,100). To ensure ST is completed at the correct loads, athletes may undertake 1RM testing for primary exercises regularly. As demonstrated by Baldwin et al., CE and RE significantly improved after ST implementation with a 3-second controlled focus on the eccentric phase of each exercise and the concentric phase completed as fast as possible in LD triathletes. In addition, recent literature also demonstrates a high correlation between eccentric strength and RE, further emphasizing the importance of prescribing ST with an eccentric focus (56).

To encourage improvements in RFD, exercises should also be prescribed with a focus on intended (rather than actual) velocity of movement during the concentric phase of each exercise (44,81); however, improvements in RFD may still occur from heavy ST without this focus on velocity (1). Before lifting heavy loads with an eccentric focus, it is recommended that athletes focus on the technique

Table 4
Example strength training session with a cycle focus for long distance triathletes

Exercise	Sets	Repetitions	Loads
Injury prevention			
Step ups/downs	3	8	Bodyweight
Walking lunge	3	8 each leg	2 × 5–10 kg dumbbells
SL deadlifts	3	8 each leg	2 × 5–10 kg dumbbells
Performance/strength[a]			
Deadlift	3	6	85% of 1RM
Back squat	3	6	85% of 1RM
Split squat	3	6	85% of 1RM
Single leg seated calf raise	3	6	85% of 1RM

[a]All performance/strength exercises completed with a 3-second eccentric lower, as fast as possible concentric phase. If the athlete is new to strength training or accumulating excessive fatigue, decrease the number of performance heavy strength exercises as appropriate.

of more basic exercises and gradually progress to eccentric movements (56). It is recommended that athletes commence ST with lighter loads and progressively build to heavy ST loads to minimize fatigue and delayed onset muscle soreness, which may affect later endurance training sessions (81).

FREQUENCY AND DURATION

A recent meta-analysis found a significant relationship between training duration and improving the E of exercise, suggesting that as little as 6–8 weeks of ST can reduce E. Protocols consisting of more than 24 strength sessions in total displayed greater improvements in E compared with protocols that had less than 24 sessions (15). In support of this, a progressively overloaded ST session completed twice a week for 12 weeks can result in significant improvements in maximal strength, CE, and RE in LD triathletes (58). If the athlete is in peak competition period or is focusing on other aspects of endurance training, it is important not to cease ST to maintain benefits gained from concurrent training. One ST session per week for 20 weeks may be substantial enough to maintain improvements in strength if the intensity and therefore load of each ST session is maintained (10,11,78). Table 6 outlines an example periodized ST program for differing phases of the racing season.

Table 5
Example strength training session with a run focus for long-distance triathletes

Exercise	Sets	Repetitions	Loads
Injury prevention			
Single leg deadlifts	3	8 each leg	2 × 5–10 kg dumbbells
Pelvic drops	3	12 each leg	Bodyweight
Wall slide	3	6 each leg	Bodyweight
Performance/strength[a]			
countermovement jump	3	4–8	Bodyweight
Power clean	3	6	85% of 1RM
Back squat	3	6	85% of 1RM
Single leg seated calf raise	3	6	85% of 1RM

[a]All performance/strength exercises completed with a 3-second eccentric lower, as fast as possible concentric phase except the power clean which should be completed with the concentric phase as fast as possible and the athlete taking time between each repetition to ensure good technique. If the athlete is new to strength training or accumulating excessive fatigue, decrease the number of performance heavy strength exercises as appropriate.

SCHEDULING

It should be acknowledged that although ST can significantly improve performance in triathletes, the additional training load may negatively affect the quality of subsequent endurance training sessions and potentially lead to resistance training induced suboptimization of endurance performance (RT-SEP) (26–28). To minimize RT-SEP, ST can be strategically implemented around endurance training sessions and be prescribed to account for the mode, intensity, and duration endurance training sessions. A greater recovery time may be needed when completing ST sessions after running when compared with cycling or swimming, because the eccentric muscle contractions and ground reaction forces in running induce more stress on the body. The following considerations have been outlined in recent research to help minimize RT-SEP (28):

- If possible, complete ST on a day where no endurance training is completed.
- If this is not possible, aim to complete the endurance training session first, followed by the ST session as the second session of the day. If it is not possible for the athlete to complete the endurance training first, complete the ST session first and then complete a swim or cycle session second, preferably with the swim or cycle session below anaerobic threshold

Table 6
Example periodized strength training program for long distance triathletes of a 38-week training cycle

	General building phase of training		Competition specific phase	Racing season	Taper
	0–6 wk	6–12 wk	12–24 wk	24–36 wk	36–38 wk
Frequency per week	2–3	2–3	2	1–2	1
Exercise selection[a]	2–3 injury prevention exercises, 3–4 strength exercises (Inc 1 plyometric if focusing on running)	2–3 injury prevention exercises, 3–4, strength exercises (Inc 1 plyometric if focusing on running)	2–3 injury prevention exercises, 3–4 strength exercises (Inc 1 plyometric if focusing on running)	2–3 injury prevention exercises, 3–4 strength exercises (Inc 1 plyometric if focusing on running)	1 -2 injury prevention exercises, 2–3 strength exercises (Inc 1 plyometric if focusing on running)
Injury prevention prescription	2–3 sets, 8–12 repetitions	2–3 sets, 8–12 repetitions	2–3 sets, 8–12 repetitions	2–3 sets, 8–12 repetitions	2 sets, 8–12 repetitions
Strength prescription (all exercises completed with a 3 s eccentric control phase and fast as possible concentric phase)	3–4 sets, 8–12 repetitions, ≤75% of 1RM, 90 s–3 min rec	3–4 sets, 8–12 repetitions, ≤75% of 1RM, 90 s–3 min rec	3–5 sets, 1–6 repetitions, ≥80% of 1RM, 3–5 min rec	3–5 sets, 1–6 repetitions, ≥80% of 1RM, 3–5 min rec	1–3 sets, 1–6 repetitions, ≤70% of 1RM, 3–5 min rec
Plyometric prescription	2–3 sets, 4–8 contacts each set, 90 s–3 min rec	2–3 sets, 4–8 contacts each set	2–3 sets, 4–8 contacts each set, 90 s–3 min rec	2–3 sets, 4–8 contacts each set, 90 s–3 min rec	1 - 2 sets, 4–8 contacts each set, 90 s–3 min rec

[a]Beginner triathletes and those new to strength training may decrease the number of exercises selected initially. Athletes experiencing a high level of fatigue may also want to decrease the number of exercises per session by 1–2 if needed.

Inc = including; rec = recovery; RM = repetition maximum.

(AT). If a run is scheduled on the same day as ST and for logistical reasons must be completed after the ST session, keep the intensity of the run below AT.

- Allow 6–9 hours of recovery between the completion of strength and endurance training for optimal recovery and adaptation from both sessions.
- Try to incorporate key running interval sessions (intensities above AT) 48–72 hours after a high-load volume ST session.
- Monitor levels of fatigue between strength and endurance training sessions (using HR and/or rating of perceived exertion).

Athletes and coaches may also consider the "priority concept," particularly when the athlete is not in the peak of their racing season. Using this concept, the athlete may prioritize their "weakest" link first in training. Therefore, if a particular triathlete is lacking strength, they may benefit from prioritizing this first in training and as racing season becomes closer, can focus on other aspects of training as the priority (47,66). Alternatively, as it may take a minimum of 8 weeks to see a significant improvement in physiological variables from ST interventions and because of a possible negative effect on endurance training in the initial stages of ST commencement, an athlete may prefer to refrain from commencing ST close to the date of a competition and wait until the commencement of their next season to complete concurrent strength and endurance training.

CONCLUSION

The completion of concurrent strength and endurance training for LD triathletes is recommended to improve physiological variables contributing to overall performance. Optimizing ST for LD triathletes is complex because of the nature of prescribing exercises for 3 varying disciplines each utilizing different movement patterns and muscle groups. Heavy ST should be implemented to optimize both CE and RE, whereas the addition of plyometric/explosive exercises may be included if the athlete's focus is to improve RE. Coaches should carefully program ST for individual athletes, taking into consideration their training and injury history, discipline strengths and weaknesses, fatigue, and endurance training regime. The scheduling and frequency of ST may be manipulated to minimize any potential negative side effects that ST may have on endurance training sessions and overall performance. A limitation of the current paper is the relative lack of studies that have examined ST specifically in LD triathletes and the lack of studies to assess improvements in a triathlete's physiological performance using testing methods with high task representative design.

PRACTICAL APPLICATIONS

- Identify the triathlete's strengths and weaknesses within each sporting discipline (swim, cycle, or run) and prescribe ST exercises accordingly to bias a particular discipline.
- Consider not only the athlete's performance, but also injury history and consider implementing specific strengthening exercises to address injuries as an integral part of the ST program.
- Heavy ST is recommended to improve performance in all 3 disciplines, whereas plyometric/explosive type exercises appear only beneficial in improving run performance.
- To prescribe an ST program to address all 3 disciplines, program heavy ST. The addition of 1–2 plyometric exercises may be included if run performance is prioritized.
- Periodize the ST program and consider the athlete's racing schedule in this process. A minimum of 24 ST sessions is needed for optimal performance improvements and ideally, these should be completed before peak competition time. This ST load can then be decreased to as little as 1 session per week for up to 20 weeks to maintain strength improvements.
- If completing strength and endurance sessions on the same day, complete endurance training sessions as the first session of the day and if possible and try to avoid key run interval sessions within 9–24 hours after high load ST sessions.
- The most important factor to consider when programming ST for LD triathletes is to individualize the program to be specific to each athlete's goals, injury history, likes and dislikes, and discipline strengths and weaknesses.

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