Title: Backward running; the why and how to program for better athleticism

Running head: Programming Backward Running for Athletes: The Why and How

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ABSTRACT

Backward running (BR) is a common locomotive technique used by most over-ground athletes during both competition and training, yet there are limited empirically based recommendations for using BR training for athletes. This article highlights the role of BR in sports context, provides insights into why BR may benefit athletes and recommends how to integrate BR into strength and conditioning programs. Informed guidance is provided on the practical applications for athletes, which should help speed and strength coaches design and facilitate BR in a safe and progressively overloaded fashion for youth and adult athletes alike.

Key words: conjugate method, aerobic, anaerobic, retro-running, sprint-training, contractile stimulus

7.1 Introduction

In the pursuit of optimal performance, athletes typically participate in a variety of training methods designed to reduce injury and enhance athletic outcomes. Backwards running (BR), which has been used to prepare athletes for competition demands (4, 32) and as a return to play protocol for injured athletes (24), is one such method. Although a formal definition of BR has yet to be adopted in the scientific community, Uthoff, Oliver, Cronin, Harrison and Winwood (58) defined BR as "any form of locomotion in a reverse direction where movement is accomplished through a single leg of support throughout foot-ground contact and both feet simultaneously in the air between contralateral foot strikes". Backward running is different than other forms of backward locomotion such as backward pedalling – the crouched technique often used by defensive backs in American football. Figure 7.1 provides an example of different backward running gaits. Backward running, for the purpose of this chapter, more closely emulates forward running (FR) with an upright running posture and contralateral arm swing (60). Figure 7.2 highlights the technical models adopted over the gait cycle during maximum velocity BR and FR.

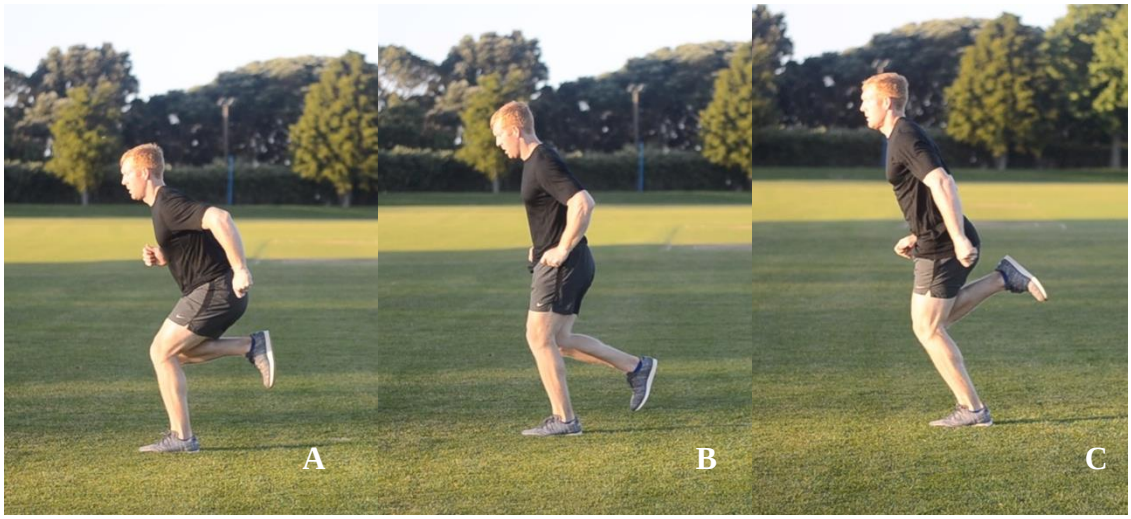

Figure 7.1. Backpedal (A), backward shuffle (B), and backward run (C) during mid-stance phase of gait.

A recent review examining the acute and trained responses to BR found that running in reverse had a unique energetic and biomechanical profile useful for enhancing a range of athletic performance measures from running economy to change of direction ability (58). Given the recent developments in literature pertaining to the use of BR for athletic enhancement in both youth and adult populations (56, 58-60), this chapter aims to examine why BR has made a resurgence in the literature and provides practical recommendations for how to integrate BR into athlete training programmes.

7.2 The Why: The Role of Backward Running in Sports and Training

Backward running is a form of locomotion which, like FR, is utilised by athletes in most overground sports (5, 37). Running itself is defined as a form of gait which is characterised by a single support phase and double flight phase (7). While both directions of locomotion are thought to be generated by the same neural pathways (25), BR is unique in that visual feedback is altered and greater demands are placed on alternative sensory systems to maintain positional awareness (25, 34). The ability to run backwards with an altered visual orientation may give athletes a tactical advantage. For example, being able to run backward at high speeds while maintaining a view of the ball or opposition will allow athletes to make more informed decisions (3). This is particularly important when you consider rugby league players BR an average of 3.6-5.4 m after each tackle (48), BR comprises of 3.4% of total distance covered by professional handball athletes during competition (36) and that elite soccer players cover 3-4% of the entire match distance running backward (37).

Outside of game play, BR is commonly included in injury prevention and rehabilitation programmes (20, 24, 27). Backward running is also part of many warm-up protocols which prepare the body for specific movements encountered during the sport and enhance athletic performance (39, 46, 49, 65). Additionally, BR has been used as a training tool

by coaches to increase qualities of aerobic and anaerobic fitness (40, 55), vertical jump height (60), change of direction performance (53, 56), and sprinting speed (60). It is important that strength and conditioning professionals understand the body's immediate response to BR and the efficacy of training using this modality so they can better integrate BR in their practice.

7.2.1 Acute Responses to Backward Running

The immediate physiological or biomechanical adaptations to a stimulus provide a snapshot of the potential long-term effects of an exercise. A number of researchers have studied the energetic, kinematic, and kinetic responses to BR, and compared these to FR. Table 7.1 provides an overview of the acute responses of BR versus FR at similar relative intensities (i.e., BR at ~70% of FR speed).

As identified in Table 7.1, researchers have shown that, at the same relative, or matched, intensity (e.g., maximal velocity or BR at 70% of FR velocity), BR is characterised by greater energetic expenditure (15, 17, 63), lower running speed (3, 59) and overall joint ROM (3, 18), unique step kinematic interactions (11, 18, 62), decreased lower limb compliance (8, 9), reliance on isometric and concentric muscle actions (8, 9) greater leg muscle activation (18, 51) reduced knee joint stress (19, 45), modified ratios of braking and propulsive forces (8, 9) and greater rates of force development (63) compared with FR. The unique physiological and biomechanical responses to BR indicate that it may provide a different training stimulus to FR, which may serve to reduce injury risk, enhance metabolic functions, and improve muscular capabilities. Furthermore, including BR into a programme while following the principles of variability, specificity and overload may serve as a conjugate method to combat training monotony.

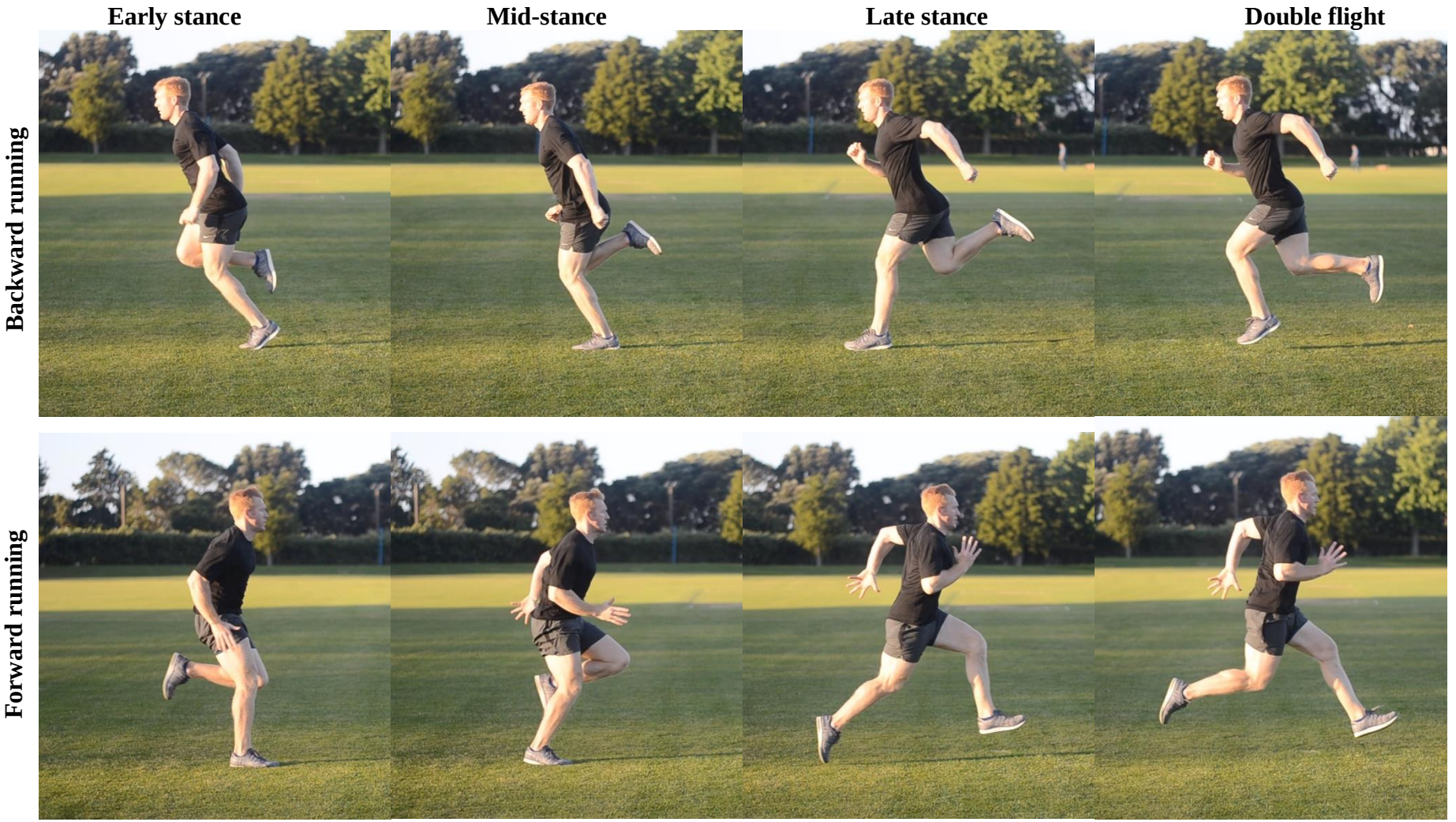

Figure 7.2. Gait cycle of backward running and forward running.

Table 7.1. Comparison of acute characteristics of forward versus backward running at matched relative running speeds

Variable	**Study**	**BR in relation to FR**
Cardiopulmonary		
Oxygen consumption	(1, 17, 63)	↑
Heart rate	(1, 17)	↑
Blood lactate	(1, 17)	↑
Kinematics		
Velocity	(3, 59)	↓
Ankle ROM	(15)	↓
Knee ROM	(15, 19)	↓
Hip ROM	(15)	↓
Stride frequency	(3, 15, 62)	↑
Stride length	(3, 62)	↓
Contact time	(62)	↑
Flight time	(62)	↓
Lower limb muscle activity	(18, 63)	↑
Eccentric muscle action	(8, 9)	↓
Isometric muscle action	(8, 9)	↑
Concentric muscle action	(8, 9)	↑
Kinetics		
Vertical leg stiffness	(8)	↑
Knee joint force	(19, 45)	↓
Vertical GRF	(62)	↓
Braking/propulsive force	(8, 9)	↓/↑
Braking/Propulsive time	(8, 9)	↓/↑
Rate of force development	(63)	↑

BR = backward running; FR = forward running

7.2.2 Backward Running as an Injury Resistance Tool

The primary goal of any strength and conditioning programme is to reduce the likelihood of injury and ensure athletes are healthy for competition (29, 54). Along these lines, BR is included in programmes specifically designed to minimise injury risk in athletes of all ages (13, 20, 49). In particular, warm ups such as FIFA 11+ (31), FIFA 11+ kids (46), HarmonKnee (27), Performance Enhancement and Injury Prevention (20), and Dynamic Warm-Up (2) provide exercise variation and progression to reduce the likelihood of sustaining an injury to the knee and ankle ligaments and thigh muscle strains. Warm up programmes including BR have been found to be particularly beneficial for reducing the amount of overuse and severe injuries in athletes between 13-20 years of age (20, 27, 49).

One rationale for including BR early into a warm up protocol or pre-season programme is that reductions in joint ROM of the lower limbs (15) while concomitantly adopting an increased stride frequency will reduce the load on lower body joints (19, 23, 45). Chronic reductions in lower limb joint loading may lead to fewer impact related musculoskeletal injuries. Further, functional reversal of the leg muscles during BR may provide a means to reduce stress on the posterior chain and reduce repetitive strain injuries (24). This is particularly important in adolescent athletes who are undergoing rapid hormonal and anthropometric changes where their training increases (29) and they must be able to withstand greater forces (35). Coaches may use BR to improve neural and musculotendinous properties of the lower limbs, while adding variety into a programme, and attenuate stress placed on the lower limbs.

7.2.3 Backward Running to Enhance Muscular Functions

The nature of athletic tasks determines the reliance on components of musculotendinous functioning. Forward running is often understood in terms of a spring mass model by which muscles are stretched and eccentric energy is absorbed and converted to propulsive energy through the tendons and connective tissue (6). Alternatively, BR more closely reflects a pendulum action whereby the muscle and tendon length remains relatively constant upon foot-ground contact and propulsion is produced primarily through a contractile movement (8, 9). Concentric-dominant exercises offer a potentially useful training tool, which may negate or mitigate muscle damage, soreness, fatigue, and inflammation associated with eccentric movements (26). The specific isometric and concentric nature of BR has led clinicians and coaches to use BR as a tool to return players back from injury (24, 33) and increase quadriceps strength (18, 53) while concomitantly reducing knee joint stress (19, 45).

Training BR leads to preferential adaptations in movements which are dependent on the concentric muscle functioning of the quadriceps, such as vertical countermovement jumps and early accelerated sprinting (60). Adolescent athletes around the time of their growth spurt seem to respond particularly well to BR, where their vertical jump ability has been found to increase by 9.9% (ES = 0.83) and their sprint performance over 0-10 m and 0-20 m improved by 7.5% (ES = 1.56) and 5.0% (ES = 1.04), respectively following training twice a week for 8-weeks. The dynamic leg extension action produced during BR may provide a method to train the anterior muscles of the thigh and hip to produce concentric force at relatively high velocities. Therefore, if the demands of a sport depend on acceleration ability or an athlete needs to improve their ability to produce concentric force, BR may provide a means to develop this component of athletic performance.

In addition to linear sprinting, BR has also been identified as a method to increase vertical leg stiffness (60) and change of direction ability in athletes (56). Uthoff et al. (60) found that 8-weeks of BR training improved vertical leg stiffness similar to equal volume and intensity training in a group of high-school male athletes (10.6% and 12.4%, respectively). Additionally, Terblanche and Venter (56) concluded that netball specific training using BR was more beneficial than equivalent FR training, with 505 agility, Agility T, and ladder tests improving between 3.4-10.3% (ES = 0.85 – 1.44) in a group of highly trained female netball athletes. These findings indicate that BR is not only a contractile stimulus, but can promote positive adaptations to fast stretch-shortening cycle tasks (57) and movements which have a large eccentric component (10) for athletes of varying ages and experience levels.

7.2.4 Backward Running as a Metabolic Stimulus

From an energetics standpoint, BR places a greater metabolic demand on individuals than FR at similar relative intensities (1, 17, 63). Essentially, this means that an athlete can perform BR at the same absolute volume and relative intensity as FR, yet expect to expend approximately 28% more energy (11). Therefore, when repeatedly exposed to BR training, athletes are able to improve their running economy between 2.5-33% (40, 55) while also improving their peak oxygen consumption capabilities by 5.3% (55). The exact mechanisms underpinning these adaptations are ambiguous and require further exploration, however, the variability of performing a novel athletic task (34) along with increased demand on the concentric functioning of muscles have been postulated to influence the specific metabolic responses to BR (8, 9). Practically, this means that athletes who are either injured, or under a high training load, can include BR into their programme to stimulate metabolic responses similar to FR with fewer repetitions.

7.3 The How: Integrated Programming

Given the highlighted research into why a strength and conditioning coach may wish to implement BR as an acute or chronic training stimulus for athletes, it is important to understand how BR may be integrated as an effective training practice. To minimise the effects of accommodation, subsequent training stagnation, the principle of variation should be applied (64). Appropriate variation is important to stimulate continued adaptations over multiple training phases (28) and is concerned with appropriate manipulation in exercise selection, speed, volume, and intensity (52). Similarly, when an athlete is learning a new skill, there needs to be a sequence of progressions that allow them to become habituated with the movement and master the basics at lower intensities before advancing to higher intensity or more complex movements (40). Therefore, we recommend that coaches use BR as a method to vary exercise selection and it should be progressed in order of running speed, absolute and relative volume, and finally, by adding external resistance. The following sections provide recommendations for how to progressively integrate different modes of BR into an athlete's training programme. Please note that while it is important to consider exercise selection, speed, volume, and appropriate resistance for both purposes of injury rehabilitation and athletic performance, the following programme suggestions are focused on healthy, uninjured, athletes. However, we recommend any coach wishing to use BR as a return to play protocol to adhere to the principle of variation and confer with their physiotherapist or team physician for programming considerations.

7.3.1 Phase 1: Progress Backward Running Speed

Due to the increased coordination demands (34) and modifications to sensory inputs during BR (25, 34), running backwards at speed should be introduced gradually into an athlete's training programme and, where possible, be performed on soft surfaces such as

grass. This is especially important if an athlete is young or has limited training history with BR as they may have more variable coordination ability (16, 44). The programme presented in this section is designed to habituate an athlete to high-speed BR at commonly used speed ranges of 40-55%, 60-75% and +90% of maximum running velocity (59).

Table 7.2. 2-week introductory backward running programme.

Training phase	**General preparation**			
Speed emphasis	Familiarisation			
Progression emphasis	Speed			
Week	1		2	
Training session	1	2	3	4
	Repetitions	Repetitions	Repetitions	Repetitions
Slow (40-55%)	10	8	6	5
Moderate (60-75%)	5	5	6	6
Fast (90+%)	0	2	3	4
Distance (m)	15 - 20	15 - 20	15 - 20	15 - 20
Total volume (m)	225 - 300	225 - 300	225 - 300	225 - 300
Cue	High	Moderate	Low	None

An introductory programme such as that detailed in Table 7.2 may be conducted over a microcycle of two weeks with training conducted biweekly. As running speed is increased, special attention should be given to the technical running model using ability appropriate cues similar to those found in Table 7.3 and feedback on running times. As speed is progressed, the amount of feedback on running times may be reduced to allow athletes to autoregulate their speeds. Based on our previous work (59), it takes male athletes between the ages of 15-18 years of age approximately three sessions to become accustomed to self-selecting BR and FR speeds consistently between sessions. Overload in this manner serves to both enhance proficiency and confidence in performing high-speed BR, and refine autoregulatory capabilities of athletes.

Table 7.3. Cues for backward running technique

1. Slight flexion at the hip
2. Push explosively through the ball of the foot on the ground
3. Use similar arm action to forward running, i.e. contralateral arm/leg action
4. High heel recovery of the swing leg
5. Extend the swing leg behind by kicking and reaching rapidly

7.3.2 Phase 2: Progress Backward Running Volume

Once an athlete is familiar with BR at high intensities and can accurately selfselect running speeds with minimal to no external feedback, the second phase is to overload BR by modifying either relative or total running volume. Respectively, this means a speed or strength coach can either manipulate the distance travelled at each intensity, or the sum of all intensities for total session load. Based on current evidence from both youth and adult research, free, or unresisted, sprint programmes should be performed 2-3 times a week for >6 weeks and comprise of approximately 16 runs over ~15-30 m per session (38, 47). These programming guidelines have also been found to lead to positive adaptations after BR (60). Therefore, the training programme presented in this section is designed to improve performance and lower body stretch shorten cycle function by progressively increasing both forms of volume (60).

Table 7.4 exemplifies how an 8-week programme can be structured during a transition from the general preparatory phase into the specific preparatory phase with an emphasis on developing speed-strength. To standardise the programme, lower intensity runs are performed before higher intensities. Volume is progressed first by increasing the number of moderate and fast repetitions over the course of the first 4-weeks while maintaining the same total session volume. Second, using a similar relative loading scheme to the first

Table 7.4. Sample off-season unresisted backward running programme

Training phase	**General preparation**								**Specific preparation**							
Speed emphasis	Speed strength															
Progression emphasis	Relative and absolute volume															
Week	1		2		3		4		5		6		7		8	
Session	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Repetitions Slow (40-55%)	3	3	2	2	1	2	1	1	3	3	2	2	1	2	1	1
Repetitions Moderate (60-75%)	4	3	4	3	4	2	3	2	4	3	4	3	4	2	3	2
Repetitions Fast (+90%)	8	9	9	10	10	11	11	12	8	9	9	10	10	11	11	12
Distance (m)	15	15	15	15	15	15	15	15	20	20	20	20	20	20	20	20
Session volume (m)	225	225	225	225	225	225	225	225	300	300	300	300	300	300	300	300

4-weeks, running distance is increased by five metres for each run, which leads to an increase in total session volume for weeks 5 - 8. To ensure the acute expression of muscular power is maintained, fast repetitions (+90% max effort) should include rest intervals of three to five minutes (14). Understanding how BR can be progressed using volume manipulation is useful to strength and conditioning professionals and provides a foundation for adding external load to BR in the form of resisted runs.

7.3.3 Phase 3: Progressive Backward Running Using Resistance

Once an athlete has undergone training phases progressing BR speed and volume, external load can be added in the form of resisted sled towing. Resisted sled towing is a form of unilateral strength training (30) which adheres to the principle of specificity to improve sprinting performance and lower body power (12, 41). Inclusion of unilateral movements is essential given that when athletes perform linear running or change of direction movements, they will predominantly be in a single-leg support during the action (50). Furthermore, variable unilateral multidirectional movements have been shown to improve change of direction ability and multidirectional jumping ability compared to traditional bilateral exercises (21).Therefore, integrating backward sled towing into an athlete's training programme is recommended as a means to aid metabolic and neuromuscular functioning (43, 61).

The programme in Table 7.5 demonstrates how an 8-week resisted BR programme can be structured during the transition from a specific preparatory phase into a pre-competition phase with an emphasis on developing strength-speed for accelerated sprinting. The programme follows the recommendations that resisted sprint training focused on acceleration performance should be conducted 2 – 3 times per week for >6 weeks with loads >20% body mass (41). As resisted sprinting maximal expression of muscular power, interset rest of three to five minutes is recommended to ensure maximal

motor unit activation and maintenance of training intensity (14). The use of daily undulated loading is used to add novelty and variability to the programme (22), whereas the principle of progressive overload is adhered to by increasing resistance each week. The concentric muscle demands of sled towing (43) in combination with BR provide a method to strengthen contractile muscle function.

7.3.4 Backward Running as Part of a Total Performance Plan

Although the preceding programmes have been recommended for improving running, jumping, and hopping performance in athletes (60), by no means are they the only way to integrate BR into an athlete's training programme. By understanding the underpinning mechanisms of BR, an informed coach/clinician can adapt the programmes any number of ways to meet the demands of the sport or requirements of the athlete. Similar to any other training method, BR should not be performed in isolation and instead as part of a wider strength and conditioning programme that includes a range of training modalities. It is therefore recommended that strength and conditioning coaches include strength, multi-directional running, and ballistic movements because these combinations will provide concurrent training adaptations to muscle force capabilities, stretch-shortening cycle functioning, and metabolic fitness (42). Furthermore, BR may be implemented into regular warm-ups as a time effective method to reduce injury and enhance performance, or into a traditional FR sprint programme on acceleration days as a conjugate method to increase movement variability. Although further research still needs to be performed to identify the optimal application of BR, when it is included as part of a youth athlete development or sport-specific training programme it may reduce injury risk and promote beneficial adaptations across a wide variety of athletic performance tasks dependent on lower body power, speed, and metabolic fitness (20, 40, 56, 60).

Table 7.5. Sample off-season resisted backward running programme.

Training phase	**Specific preparation**										**Pre competition**					
Speed emphasis	Strength speed															
Progression emphasis	Load relative to body mass															
Week	1		2		3		4		5		6		7		8	
Session	1	2	3	4	5	6	7	8	9	10	1	2	3	4	15	16
Repetitions	6	6	7	7	8	8	9	9	6	6	7	7	8	8	9	9
Load	20%	30%	25%	35%	30%	40%	35%	5%	30%	40%	35%	45%	40%	50%	45%	55%
Distance (m)	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Distance per session (m)	90	90	105	105	120	120	135	135	90	90	105	105	120	120	135	135
Weekly distance (m)	180		210		240		270		180		210		240		270	

7.4 Conclusion

Given the rigours of sport, coaches are constantly looking for effective training strategies to improve their athletes' performance while concomitantly minimising joint loading. As evidenced previously, BR could be a means of aerobic, anaerobic, and neuromuscular training that does not overload tendons and ligaments as much as FR. Importantly, this chapter is not intended to understate the importance of training FR, nor is BR a panacea for injury prevention or athletic performance, but rather a method in a practitioner's toolkit. Similar to other forms of strength and speed training, BR should be practiced and progressed appropriately. Depending on the competence and goals of the athlete and current training phase, different BR modalities may be used to apply the principles of variation, specificity, and overload. Integrating BR as part of a holistic athlete development programme may provide a novel stimulus which brings physiological and physical adaptations that compliment an athlete's ability, serves to increase training variability, and stave off the monotony of traditional training.

References

1. Adesola AM and Azeez OM. Comparison of cardio-pulmonary responses to forward and backward walking and runnin. *Af J Biomed Res* 12: 95-100, 2009.
2. Aguilar AJ, DiStefano LJ, Brown CN, Herman DC, Guskiewicz KM, and Padua DA. A dynamic warm-up model increases quadriceps strength and hamstring flexibility. *J Strength Cond Res* 26: 1130-1141, 2012.
3. Arata A. Kinematic and kinetic evaluations of high speed backward running, in: *The department of the air force*. University of Oregon, 1999, p 119.
4. Ayala F, Calderón-López A, Delgado-Gosálbez JC, Parra-Sánchez S, Pomares-Moguera C, Hernández-Sánchez S, López-Valenciano A, and De Ste Croix M. Acute effects of three neuromuscular warm-up strategies on several physical performance measures in football players. *PLoS ONE* 12: e0169660, 2017.
5. Bates BT, Morrison E, and Hamill J. A comparison between forward and backward running. Presented at The 1984 Olympic Scientific Congress Proceedings:Biomechanics, Eugene, Oregon, 1984.
6. Blickhan R. The spring-mass model for running and hopping. *J Biomech* 22: 1217-1227, 1989.
7. Cappellini G, Ivanenko YP, Poppele RE, and Lacquaniti F. Motor patterns in human walking and running. *J Neurophysio* 95: 3426-3437, 2006.
8. Cavagna GA, Legramandi MA, and La Torre A. Running backwards: soft landing-hard takeoff, a less efficient rebound. *Proceedings of Biologicial Sciences* 278: 339-346, 2011.
9. Cavagna GA, Legramandi MA, and La Torre A. An analysis of the rebound of the body in backward human running. *J Exper Biol* 215: 75-84, 2012.
10. Chaabene H, Prieske O, Negra Y, and Granacher U. Change of direciton speed: toward a strength training approach with accentuated eccentric muscle actions. *Sports Med* 48: 1773-1779, 2018.
11. Conti CA. The mechanical determinats of energetic cost in backward running, in: *Kinesiology: Execise Science/ Wellness Mangement*. Humboldt State University, 2009.
12. Cross MR, Brughelli M, Samozino P, Brown SR, and Morin JB. Optimal loading for maximizing power during sled-resisted sprinting. *Int J Sport Physio Perf* 12: 1069-1077, 2017.
13. Daneshjoo A, Mokhtar A, H, Rahnama N, and Yusof A. Effectiveness of injury prevention programs on developing quadriceps and hamstrings strength of young male professional soccer players. *J Hum Kinet* 39: 115-125, 2013.
14. de Salles BF, Simão R, Miranda F, da Silva Novaes J, Lemos A, and Willardson JM. Rest interval between sets in strength training. *Sports Med* 39: 765-777, 2009.
15. DeVita P and Stribling J. Lower extremity joint kinetics and energetics during backward running. *Med Sci Sport Exerc* 23: 602-610, 1991.
16. Floria P, Sanchez-Sixto A, Ferber R, and Harrison AJ. Effects of running experience and its variability in runners. *J Sports Sci* 36: 272-278, 2017.
17. Flynn TW, Connery SM, Smutok MA, Zeballos RJ, and Weisman IM. Comparison of cardiopulmonary responses to forward and backward walking and running. *Med Sci Sport Exerc* 26: 89-94, 1994.

18. Flynn TW and Soutas-Little RW. Mechanical power and muscle action during forward and backward running. *J Orthop Sport Phy Ther* 17: 108-112, 1993.
19. Flynn TW and Soutas-Little RW. Patellofemoral joint compressive forces in forward and backward running. *J Orthop Sport Phy Ther* 21: 277-282, 1995.
20. Gilchrist J, Mandelbaum BR, Melancon H, Ryan GW, Silvers HJ, Griffin LY, Watanabe DS, D RW, and Dvorak J. A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *Am J Sport Med* 36: 1476-1483, 2008.
21. Gonzalo-Skok O, Tous-Fajardo J, Valero-Campo C, Berzosa C, Bataller AV, Arjol-Serrano JL, Moras G, and Mendez-Villanueva A. Eccentric-overload training in team-sport functional performance: constant bilateral vertical versus variable unilateral multidirectional movements. *Int J Sport Physio Perf* 12: 951-958, 2017.
22. Harries SK, Lubans DR, and Callister R. Systmatic review and meta-analysis of linear and undulating periodized resistance training programs on muscular strength. *J Strength Cond Res* 29: 1113-1125, 2015.
23. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, and Ryan MB. Effects of step rate manipulation on joint mechanics during running. *Med Sci Sports Exerc* 43: 296-302, 2011.
24. Heiderscheit BC, Sherry MA, Silder A, Chumanov ES, and Thelen DG. Hamstring strain injuries: recommendations for diagnosis, rehabilitation, and injury prevention. *J Orthop Sports Phys Ther* 40: 67-81, 2010.
25. Hoogkamer W, Meyns P, and Duysens J. Steps forward in understanding backward gait: From basic circuits to rehabilitation. *Exerc Sport Sci Rev* 42: 23-29, 2014.
26. Hunter G. Muscle physiology, in: *Essentials of Strength Training and Conditioning*. T Beachle, R Earle, eds. Champaign, IL: Human Kinetics, 2000, pp 3-12.
27. Kiani A, Hellquist E, Ahlqvist K, Gedeborg R, Michaélsson K, and Byberg L. Prevention of soccer-related knee injuries in teenaged girls. *Arch Intern Med* 170: 43-49, 2010.
28. Kraemer WJ. A series of studies: The physiological basis for strength training in Amercian football: Fact over philosophy. *J Strength Cond Res* 11: 131-142, 1997.
29. Lloyd RS, Cronin JB, Faigenbaum AD, Haff GG, Howard R, Kraemer WJ, Michell LJ, Myer GD, and Oliver JL. National strength and conditioning association position statement on long-term athletic development. *J Strength Cond Res* 30: 1491-1509, 2016.
30. Lockie RG, Murphy AJ, Schultz AB, Knight TJ, and Janse de Jonge XAK. The effects of different speed training protocols on sprint acceleration kinematics and muscle strength and power in field sport athletes. *J Strength Cond Res* 26: 1539-1550, 2012.
31. Longo UG, Loppini M, Berton A, Marinozzi A, Maffulli N, and Denaro V. The FIFA 11_ program is effective in preventing injuries in elite male basketball playes: a cluster randomized controlled trial. *Am J Sports Med* 40: 96-1005, 2012.
32. Magalhães T, Ribeiro F, Pinheiro A, and Oliveira J. Warming-up before sporting activity improves knee position sense. *Phys Ther Sport* 11: 86-90, 2010.
33. Mattacola CG and Dwyer MK. Rehabilitation of the ankle after acute sprain or chronic instability. *J Athl Train* 37: 413-429, 2002.

34. Mehdizadeh S, Arshi AR, and Davids K. Quantifying coordination and coordination variability in backward versus forward running: Implications for control of motion. *Gait Posture* 42: 172-177, 2015.
35. Meyers RW, Sylvia M, Oliver JL, Hughes MG, Cronin JB, and Lloyd RS. Lower limb stiffness and maximal sprint speed in 11-16-year-old boys. *J Strength Cond Res* Published Ahead of Print, 2018.
36. Michalsik LB, Aagaard P, and Madsen K. Locomotion characteristics and match-induced impairments in physical performance in male elite team handball players. *Int J Sport Sci* 34: 590-5999, 2013.
37. Mohr M, Krustrup P, and Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. *J Sports Sci* 21: 519-528, 2003.
38. Moran J, Sandercock G, Rumpf MC, and Parry DA. Variation in responses to sprint training in male youth athletes: A meta-analysis. *Int J Sport Med* 38: 1-11, 2017.
39. Olsen OE, Myklebust G, Engebretsen L, Holme I, and Bahr R. Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. *BMJ* 330: 449-452, 2005.
40. Ordway JD, Laubach LL, Vanderburgh PM, and Jackson KJ. The effects of backwards running training on forward running economy in trained males. *J Strength Cond Res* 30: 763-767, 2016.
41. Petrakos G, Morin JB, and Egan B. Resisted sled sprint training to improve sprint performance: a systematic review. *Sports Med* 46: 381-400, 2016.
42. Petré H, Löfving P, and Psilander N. The effect of two different concurrent training programs on strength and power gains in highly-trained individuals. *J Sport Sci Med* 17: 167-173, 2018.
43. Pollitt DJ. Sled dragging for hockey training. *Strength Cond J* 25: 7-16, 2003.
44. Rommers N, Mostaert M, Goossens L, Vaeyens R, Witvrouw E, Lenoir M, and D'Hondt E. Age and maturity related differences in motor coordination among male elite youth soccer players. *J Sports Sci* Epub ahead of print: 1-8, 2018.
45. Roos PE, Barton N, and van Deursen RWM. Patellofemoral joint compression forces in backward and forward running. *J Biomech* 45: 1656-1660, 2012.
46. Rössler R, Donath L, Bizzini M, and Faude O. A new injury prevention programme for children's football - FIFA 11+ Kids - can improve motor performance: A cluster-randomised controlled trial. *J Sports Sci* 34: 549-556, 2016.
47. Rumpf MC, Lockie RG, Cronin JB, and Jalilvand F. The effect of different sprint training methods on sprint performance over various distances: A brief review. *J Strength Cond Res*, 2016.
48. Sirotic AC, Knowles H, Catterick C, and Coutts AJ. Positional match demands of professional rugby league competition. *J Strength Cond Res* 25: 3076-3087, 2011.
49. Soligard T, Myklebust G, Steffen K, Holme I, Silvers H, Bizzini M, Junge A, Dvorak J, Bahr R, and Andersen TE. Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. *Br Med J*: 1-9, 2008.
50. Spiteri T, Nimphius S, Hart NH, Specos C, Sheppard JM, and Newton RU. The contribution of strength characteristics to change of direction and agility perofrmance in female basketball athletes. *J Strength Cond Res* 28: 2415-2423, 2014.

51. Sterzing T, Frommhold C, and Rosenbaum D. In-shoe plantar pressure distribution and lower extremity muscle activity patterns of backward compared to forward running on a treadmill. *Gait Posture* 46: 135-141, 2016.
52. Stone MH, Collins D, Plisk S, Haff GG, and Stone ME. Training principles: Evaluation of modes and methods of resistance training. *Strength Cond J* 22: 65-76, 2000.
53. Swati K, Ashima C, and Saurabh S. Efficacy of backward training on agility and quadriceps strength. *Elix Hum Physio* 53: 11918-11921, 2012.
54. Talpey SW and Siesmaa EJ. Sports injury prevention: the role of the strength and conditioning coach. *Strength Cond J* 39: 14-19, 2017.
55. Terblanche E, Page C, Kroff J, and Venter RE. The effect of backward locomotion training on the body composition and cardiorespiratory fitness of young women. *Int J Sport Med* 26: 214-219, 2005.
56. Terblanche E and Venter RE. The effect of backward training on the speed, agility and power of netball players. *S Afr J Res Sport Phy Ed Rec* 31: 135-145, 2009.
57. Turner AN and Jeffreys I. The stretch-shortening cycle: proposed mechanisms and methods for enhancement. *Strength Cond J* 32: 87-99, 2010.
58. Uthoff A, Oliver J, Cronin J, Harrison C, and Winwood P. A new direction to athletic performance: Understanding the acute and longitudinal responses to backward running. *Sports Med* 48: 1083-1096, 2018.
59. Uthoff A, Oliver J, Cronin J, Winwood P, and Harrison C. Prescribing target running intensities for high-school athletes: can forward and backward running performance be autoregulated? *Sports* 6: 1-10, 2018.
60. Uthoff A, Oliver JL, Winwood PW, Harrison C, and Cronin JB. Sprint-specific training in youth: backward running versus forward running training on speed and power measures in adolescent male athletes. *J Strength Cond Res* Published ahead of print, 2018.
61. West DJ, Cunningham DJ, Finn CV, Scott PM, Crewther BT, Cook CJ, and Kilduff LP. The metabolic, hormonal, biochemical, and neuromuscular function responses to a backward sled drag training session. *J Strength Cond Res* 28: 265-272, 2014.
62. Weyand PG, Sandell RF, Prime DN, and Bundle MW. The biological limits to running speed are imposed from the ground up. *J Appl Physiol* 108: 950-961, 2010.
63. Wright S and Weyand PG. The application of ground force explains the energetic cost of running backward and forward. *J Exp Biol* 204: 1805-1815, 2001.
64. Zatsiorsky VM. *Science and Practice of Strength Training.* Champaign, IL: Human Kinetics, 1995.
65. Zois J, Bishop D, and Aughey R. High-intensity warm-ups: Effects during susequent intermittent exercise. *Int J Sport Physio Perf* 10: 498-503, 2015.