A new direction to athletic performance: Understanding the acute and longitudinal responses to backward running

Short title/running head: Backward running: a new perspective to athletic performance

Corresponding Author:

Aaron Uthoff, MSc, CSCS

Tel: +64 7 578 4029

Fax: +64 7 578 4853

Email: uthoffaaron@gmail.com

Authors:

Aaron Uthoff[1], Jon Oliver[1,2], John Cronin[1,3], Craig Harrison[1] and Paul Winwood[1,4]

[1]Sports Performance Research Institute New Zealand (SPRINZ)

AUT Millennium

AUT University

Auckland

New Zealand

[2]Youth Physical Development Unit

School of Sport

Cardiff Metropolitan University

Cyncoed Campus

Cyncoed Road

Cardiff CF23 6XD

United Kingdom

[3]School of Health and Medical Science
Edith Cowan University
Perth
Australia

[4]Department of Sport and Recreation
School of Applied Science
Toi Ohomai Institute of Technology
Tauranga
New Zealand

Key Points

1. The acute effects of backward running display unique cardiorespiratory and biomechanical responses compared to forward running. While running backward appears to be demanding on the cardiorespiratory system and require high total activation of lower limb muscles it has been shown to display less mechanical strain on the knee joint when compared to forward running

2. Research suggests that implementing backward running into longitudinal athletic training programs is associated with decreased injury prevalence, increased lower limb strength, and improved change of direction performance

3. Though the acute and longitudinal benefits of backward running are many, it is currently under-represented in scientific literature when compared to other forms of locomotion

Abstract

Backward running (BR) is a form of locomotion which occurs in short bursts during many overground field and court sports. It has also traditionally been used in clinical settings as a method to rehabilitate lower body injuries. Comparisons between BR and forward running (FR) have led to the discovery that both may be generated by the same neural circuitry. Comparisons of the acute responses to FR reveal that BR is characterised by a smaller ratio of braking to propulsive forces, increased step frequency, decreased step length, increased muscle activity, and reliance on isometric and concentric muscle actions. These biomechanical differences have been critical in informing recent scientific explorations which have discovered that BR can be used as a method for reducing injury and improving a variety of physical attributes deemed advantageous to sports performance. This includes, improved lower body strength and power, decreased injury prevalence, and improvements in change of direction performance following BR training. The current findings from research help improve our understanding of BR biomechanics and provide evidence which supports BR as a useful

method to improve athlete performance. However, further acute and longitudinal research is needed to better understand the utility of BR in athletic performance programs.

1 Introduction

It is understood that forward running (FR) is a propulsive form of locomotion characteristic of most overground sports. Running in humans is a method of terrestrial locomotion which can refer to a variety of speeds ranging from jogging to sprinting. Running is unique to other forms of terrestrial locomotion i.e. walking or skipping, as it is characterized by a single leg supporting the body for the duration of foot-ground contact and periods of time when both feet are in the air [1]. Superior FR speed is considered an important component of success in most overground sports [2-4]. Therefore, it is no surprise then that FR has received much attention from both scientific and coaching communities. Research on FR ranges from acute deterministic biomechanical studies [5-10] to assessments of longitudinal training studies [11-14]. Descriptive research on acute variables that characterise superior forward distance running and sprint-running performances have helped inform training methodology designed to improve running velocity and running economy [15-18]. For example, specific and non-specific training methods have been developed to enhance force production, power output, and movement velocity, which are known biomechanical determinants of FR performance in both youth and adult populations [19-21]. However, while FR has received most of the attention, other directions of locomotion, such as backward running (BR), have been less well researched.

In the absence of any formal definition of BR in the literature, BR in the context of this paper is defined as any form of locomotion in a reverse direction where movement is accomplished via a single leg of support throughout foot-ground contact and both feet simultaneously in the air between contralateral foot strikes. BR, like FR, occurs for short periods of time during many overground sports [22]. A fundamental difference between BR and FR is the visual perspective of the runner. During BR, an athlete must rely on alternative sensory information due to a lack of visual guidance experienced during FR [23, 24]. BR and derivatives, such as backpedaling, are basic movement patterns utilized for agility actions in sports [25]. BR provides athletes with a strategy to move in a desired direction and maintain a view of the ball or opposition [26], while reducing strain on the knee joint [27-29]. It has also been recommended for use in sports training programs to increase variability [30], prepare athletes for the demands of competition [31, 32], reduce injury rates [33-35] and enhance performance [30, 36-40].

Although BR may alter the normal visual orientation relative to FR, it is a strategy used by athletes of all levels. For example, elite soccer players spend approximately 3-4% of the match running backward [22]. This is interesting when you consider that the same elite soccer players only spend between 0.9 and 1.4% of the match sprinting forward. In addition, top-class soccer players (ranked 1-10 on the official FIFA list) spend significantly more time ($p < 0.05$) running backward than moderately ranked soccer players (ranked higher than 20 on the official FIFA list) [22]. This suggests that BR can be employed as a useful strategy among high performing soccer athletes.

Human locomotion is produced via central pattern generators i.e. an intraspinal network of neurons capable of generating a rhythmic output [41]. It is generally accepted that forward and backward walking are products of the same central pattern generators [23], although some contention exists about which pathways are responsible for producing each direction of locomotion [23, 42]. While limited evidence exists for whether this phenomenon extends to BR and FR [24], researchers have suggested that training adaptations from BR may transfer to FR [23]. Although a shared neural circuitry might produce each running direction, BR velocities are known to be slower than FR velocities during maximal efforts [26, 43]. In fact, maximal velocities which can be achieved during BR are approximately 70% of those which can be produced during FR [26, 43].

Although velocities achieved during BR are lower than those observed during FR, BR is found in warm-up programs designed to reduce injury prevalence and improve athletic performance [32-35, 40]. The rationale for the inclusion of BR in the warm-up has not been documented to the knowledge of these authors, however, it may be due to BR's ability to demonstrate lower biomechanical strain on the knee joint than FR [27-29, 44] while also requiring higher activation in the leg muscles [36] or simply to warm up the muscles specific to the movement patterns encountered in the sport.

Currently, BR is a movement utilized as an injury prevention method and injury rehabilitation technique [45-48], yet little is known about the athletic benefits of BR. Therefore, the purposes of this review are to (i) explore and compare the acute responses of BR to FR; (ii) examine the effects of BR training on aspects of athletic performance; (iii) discuss the possible merits of BR as a method to improve athletic performance; and (iv) provide future research recommendations into BR.

2 Search Strategy for Acute and Training Studies

From December 2016 to September 2017 a comprehensive search of seven electronic databases (MEDLINE [EBSCO], OVID, PubMed, ScienceDirect, SPORTDiscus, Web of Science and Google Scholar) was performed. The same databases were searched in January 2018 to identify more recent articles of relevance. The following keywords were used: 'backward', 'retro' 'running', 'backpedal'.

2.1 Selection Method and Criteria

Results were limited to human studies, academic journals, reviews, and dissertations. The bibliographies of all reviewed articles were hand searched and forward citation was used where applicable. All studies conducted on BR which were published in the English language were included. The study selection process involved removing duplicates, screening for relevance on title and then abstract and finally screening the full-text articles using the inclusion/exclusion criteria.

3 Acute Responses to Backward Running versus Forward Running

An acute response can refer to a range of biomechanical or physiological effects either during or immediately following a stimulus. To realise the potential long term training effects of an exercise, it is important to understand the immediate overt and underlying outcomes associated with that movement. Running research has typically aimed to identify the influence of speed [49-52] and resistance [21, 53] on acute responses, while generally overlooking the effect of running direction on these deterministic variables. Herein, acute energetic and biomechanical comparisons are drawn between FR and BR. Figure 1 provides a visual comparison between BR and FR over the stance phase of the gait cycle.

PLEASE INSERT **Figure 1.** Stance phase of backward and forward running *about here.*

3.1 Energetics and cardiopulmonary responses

The energetic cost of running overground is determined by the volume of active muscle necessary to propel an athlete in their desired direction [54], the ability of muscle tendon units to store and utilize mechanical energy [55], and the rate at which force can be applied during foot-ground contact [54, 56]. It is important to consider these factors when comparing how much energy is required during FR compared to BR.

It has been reported that BR places greater metabolic demands on the body than FR at relative and absolute velocities [54, 57, 58]. Variables assessing energetic and cardiopulmonary responses include indirect calorimetry [59], oxygen consumption, heart rate, and blood lactate concentrates [54, 57, 58]. Measurements of indirect calorimetry revealed that BR elicits 28% higher metabolic cost compared to FR at 2.24 ms^{-1} [59]. Oxygen consumption, heart rate and blood lactate have also been reported to be significantly higher during BR than FR at 2.68 ms^{-1} [57, 58]. This suggests that BR elicits a greater energetic demand and cardiopulmonary response than FR at a given speed.

Wright and Weyand [54] concluded that greater energetic demands exhibited during BR were a result of a 14% increase in average muscle force per unit of ground force exerted during BR versus FR. This resulted in 10% more muscle volume being activated to produce each unit of ground force during BR compared to FR. These findings are reported at relatively slow running speeds between 1.75 - 3.5 ms^{-1}. Currently it is unknown whether comparisons of BR and FR at running speeds greater than 3.5 ms^{-1} will result in similar reports of greater muscle volume being activated during BR.

Another suggestion for why BR requires greater energetic demands is that it is less reliant on the stretch-shortening cycle [60, 61]. Cavagna et al. [60] concluded that BR relies less on eccentric work and more on concentric work because the muscle-tendon units are stretched more slowly during the braking phase at the beginning of foot-ground contact and shorten more rapidly during the push at the end of foot-ground contact compared to FR at similar absolute velocities. Accordingly, BR appears to be more reliant on the contractile components of the motor unit, which are known to require greater energy expenditure [62, 63]. Therefore, BR is characterised by greater metabolic energy expenditure when muscles are exerting greater forces during concentric contractions and lower forces during eccentric contractions.

The time available for developing force is important for determining the energetic cost of a movement [64]. A simple inverse relationship exists between the rate of energy used for running and the time a foot applies force to the ground during each stride [55]. Wright and Weyand [54] concluded that the application of ground force during both BR and FR explains the energetic cost regardless of direction. Furthermore, they concluded that the rate at which force can be applied during foot-ground contact is higher during BR than FR [54]. This finding has relevance to sporting applications because we know that rate of force development seems to be primarily determined by the capacity of motor units to produce maximal activation in the early phase of explosive contractions (first 50-75 ms) [65].

3.2 Kinematics

Running kinematics are biomechanical variables which describe motion of the body (e.g., angles, velocities and positions), without reference to the underlying forces that cause the motion [66]. Detailing kinematics during running is useful as the information provides overt visual and quantifiable descriptions of movement. Typical kinematic measures of running include joint kinematics (e.g., location and orientation of body segments) and step kinematics (i.e. contact time, flight time, stride length and stride frequency). Empirical research pertaining to kinematic characteristics of FR and sprinting, and the influence of training on these variables, is plentiful (for review, readers are referred to the articles of: Mero et al. [10, 67], Novacheck [68]). Unfortunately, relatively little information is available on the kinematics of BR.

3.2.1 Joint kinematics. It appears that BR displays distinct differences (see Figure 2) in the displacement of the lower limbs compared to FR [26, 29, 69]. Differences can be attributable to the reversal of movement direction and the location and magnitude of joint displacements over a stride cycle [29, 69].

PLEASE INSERT Fig 2. Joint kinematics of backward running in relation to forward running [26, 29, 69]. The differences shown are relative to forward running. *about here*

ROM = range of motion

BR = backward running

FR = forward running

3.2.1.1 Ankle range of motion. From the time a runner leaves the ground until mid-way through the flight phase of their stride, ankle kinematics display similar ranges of motion (ROM) for both FR and BR [69]. However, differences appear moments before ground contact of the foot, characterised by a dorsiflexed position during FR and a second plantarflexion phase during BR [69]. Mean ankle range of motion over a stride cycle has been reported to be 52 - 55° and 42 - 47° during FR and BR, respectively [26, 69]. One possible explanation could be that the ankle is anatomically designed to produce forward propulsion [70]. The foot is therefore functionally constrained in BR due to the angle of the ankle increasing, as opposed to decreasing before foot-ground contact in FR, limiting the overall ROM and propulsive potential of the joint [26].

3.2.1.2 Knee range of motion. Knee ROM over the gait cycle has been reported to be greater during both the flight phase and stance phase of FR compared to BR at similar absolute and relative running speeds [29, 69, 71]. BR is characterized by greater knee flexion during initial foot-ground contact and greater knee extension during late foot-ground contact compared to FR [69]. Between early and late foot-ground contact the knee undergoes less flexion during BR than is experienced during FR [69]. These findings indicate that the knee is less compliant during BR compared to FR at similar absolute intensities. A discovery from Cavagna et al. [61] that BR displays greater vertical leg stiffness compared to running at similar speeds forward supports this suggestion. Although it is unknown whether these characteristics are true when comparing BR and FR at similar relative intensities, several potential training adaptations could result from decreased knee ROM and increased vertical leg stiffness exhibited during BR. For example, increases in vertical leg stiffness may translate to greater utilization of the stretch-shortening cycle [72] and reduce deformation of the lower extremities during FR and high velocity movements such as sprint-running and change of direction tasks [52]. However, this posit has yet to be empirically tested.

3.2.1.3 Hip range of motion. Mean ROM between 27 - 42° and 40 - 69° have been observed at the hip for BR and FR, respectively [26, 69]. Increasing running velocity results in concomitant increases in hip joint displacement for both FR and BR [26]. Maximal hip flexion is rarely achieved during either FR or BR, yet maximal hip extension is only seen during FR [69]. The lower ROM displayed during BR versus FR might be a result of anterior musculotendinous structures of the hip, knee and abdomen preventing overstretching during the flight phase of the stride cycle [73]. This postulate seems logical, yet is currently untested.

3.2.2 Step kinematics. Joint kinematics are known to be related to step kinematics during running [74]. For instance, as running velocity increases joint ranges of motion become greater, which leads to concomitant changes in step kinematics i.e. longer stride length [50, 75]. Step characteristics are variables that have been used by coaches and sports scientists to assess running performance for decades [18, 68]. For example, optimal stride length has been recommended for submaximal and maximal phases of FR [6, 76, 77] and increases in stride frequency are thought to determine maximal sprint running performance [78, 79]. To gain insights into the relationship between running direction and step kinematics researchers have analysed running performances at velocities ranging from 1.85 - 6.42 ms^{-1} and 2.64 - 9.10 ms^{-1} for BR and FR, respectively [26, 36, 38, 59, 69].

Running velocity is considered a result of the interaction between stride length and stride frequency [18], with greater speeds achieved through large ground reaction forces produced during short ground contact times [43]. It has been reported that the distance between each ipsilateral foot-ground contact i.e. stride length, is significantly less during BR than FR [54], where matched absolute speeds have been reported to be 12% less [58, 69] and relative speeds 37% shorter [26, 43]. Alternatively, stride frequency has been determined to be significantly higher for BR than FR [54], with matched absolute speeds being 12% faster [58, 69] and relative speeds showing 11% higher turnover [26, 43, 80]. In BR, contact times have been found to be 19% longer at self-selected speeds [29], 9% shorter at matched absolute speeds [38] and 5% greater at relative speeds [43] compared to FR. Flight times, i.e. time which neither foot is in contact with the ground, have been shown to be lower for BR than FR by 9% and 25% when compared at matched absolute and relative running speeds, respectively [38, 43]. These findings indicate that BR is characterized by increased contact times and decreased flight times which manifest as shorter stride lengths and higher stride frequencies across a range of speeds. Stride length and flight times appear to be influenced to a greater percentage when matched at relative running speed. This may be due to greater FR velocities being achieved, as we have seen that BR is on average 30% slower than FR [26, 43]. FR appears to display advantageous step kinematics for producing higher running speeds than BR, although it is difficult to decipher the underlying determinants due to limited published studies in this area.

3.3 Function and activation of leg muscles during forward and backward running

As running speed increases, the need for greater forces to produce longer stride length and higher stride frequency appears to be controlled by increases in leg muscle activity [81]. The activation of leg muscles during human locomotion is the result of learned programming patterns generated via the central nervous system [82]. The same neurological system stimulated by afferent muscle, joint and associated tissues is believed to produce both backward and forward locomotion [23, 83-85] and has been suggested to extend to BR and FR [24]. This revelation has led to researchers investigating how the function and activation of musculotendinous structures of the lower limbs change with running direction [36, 38].

3.3.1 Muscle function. The mechanical function of leg muscles is considered to have developed in humans to propel us forward [86, 87]. The quadriceps and tibialis anterior primarily serve to attenuate eccentric braking force during early foot-ground contact while the plantar flexors, hamstrings and gluteal muscles assist in forward propulsion [49]. The functional roles of lower limb muscles are interchanged between BR and FR, whereby the anterior muscles of the legs become the primary source of propulsion and posterior muscles absorb braking forces during BR [69]. The findings of Flynn and Soutas-Little [36] support this notion with their discovery that the muscle firing patterns are unique to running direction. Specifically, BR velocity is achieved by large productions of activity during the shortening action of the quadriceps and posterior lower leg muscles. The pragmatic utility of this knowledge provides a method for reducing eccentric strain on desired musculotendinous structures of the leg, while potentially developing greater concentric contractile adaptations.

3.3.2 M*uscle activation.* If faster running velocities are related to increased muscle activity [81], FR could be expected to be characterised by greater activity than BR. However, the reality is that most lower limb muscles display greater total activation over an entire stride cycle during BR compared to FR [36, 80]. The greatest differences are present in the leg extensor/hip flexor muscles with a range between 53.3% and 189.6% greater activity over the stride cycle reported during BR compared to FR at the same absolute speed [80]. These findings are important because they are the driving force for some clinicians and researchers claiming that BR can be used to increase leg strength and power [38, 88] and restore muscle balance [36]. In addition to greater muscle activation, the average muscle force per unit ground force has been shown to be substantially higher (14%) for BR than FR [54]. The researchers suggested that this was a result of larger muscle forces at the ankle presenting during BR, which may manifest due to the average active muscle length being 4% shorter during BR than FR. This suggestion seems plausible as muscles of the lower leg have reported higher activation when length is decreased [89]. Practically, even at matched absolute speeds this means that the muscle spent 4% more time in a concentrically contracted state over the stride cycle when the subject ran backward.

3.4 Kinetics

Kinetic variables (i.e. vertical and horizontal forces) have been shown to be important measures to determine running performance [10, 50, 77, 90]. The ability to generate large forces in short periods of time characterizes fast running speeds [43, 90]. It is important to therefore quantify and compare how forces are expressed during BR and FR to understand the similarities and differences between running directions. Figure 3 illustrates some key kinetics associated with BR compared to FR.

3.4.1 Patellofemoral joint compressive forces. BR has been suggested for clinical purposes because it has been proposed to reduce the mechanical stress on the knee compared to FR at matched absolute submaximal speeds [27-29]. Using mathematical models, researchers have calculated that the compression of the patella against the femur i.e. patellofemoral joint compressive force (PFJCF) is on average 24% lower during BR than FR at relative and absolute running speeds [27-29]. The general consensus is that PFJCF is primarily influenced by knee extensor moments, which have been reported to be, on average, 72% higher in FR than BR [27-29]. Knee moments are influenced by both the magnitude and location of the ground reaction force relative to the foot [28]. Therefore, it is necessary to understand how and where forces are expressed during FR and BR to conceptualize the clinical and performance implications of each running direction.

3.4.2 Magnitude and location of ground reaction forces. Whilst PFJCF is expressed to a lower degree in BR, the magnitude and orientation of the ground reaction force have been reported to be similar during both BR and FR [28, 38]. These magnitudes at relatively low running speeds have been reported to be between 1.6 to 2.5 times body weight for BR and 2.5 to 2.7 times body weight for FR, respectively [38, 91]. Weyand et al. [43] found that peak vertical ground reaction forces during BR and FR were 2.1 and 3.6 times body weight at maximal running speeds, respectively. The FR ground reaction forces found by Weyand and colleagues [43] are in agreement with other researchers who have determined that a sprinter exerts forces in excess of 3 to 4 times their body weight during FR [10, 92]. Weyand et al. [43] explained that a possible reasoning for their finding was that running speeds at which the forces were obtained were 6.42 and 9.10 ms^{-1} for BR and FR, respectively. In addition to the magnitude of force, knowing the location of force relative to the foot is useful for determining how the forces will act upon the body.

Although ground reaction force is distributed across the entire body, the foot is the only point of contact with the ground during running where forces are both attenuated and generated via the musculoskeletal system [93]. The location of ground reaction force has been identified to be further forward on the foot at initial ground contact in BR versus FR [28]. With the functional role of the knee and ankle muscles switching between BR and FR, the implications are that ground reaction forces may be attenuated more by the ankle and foot complex, resulting in a decreased moment arm between the ground reaction force vector and the knee joint in BR. This knowledge adds to our understanding of the magnitude and location of the peak force experienced during running, yet provides little information outside of a snapshot in time. Including information about how forces are expressed before and after peak ground reaction force is experienced may enhance our understanding of how FR and BR are generated.

3.4.3 Braking and propulsive forces. Kinetic variables such as breaking and propulsive force expression and the rate at which force can be developed may serve strength and speed coaches with useful information when performance enhancement is the objective. Ground reaction forces during running change from being negative during early foot-ground contact (i.e. braking) to being positive during late foot-ground contact (i.e., propulsion) [60, 66]. Measuring the duration and magnitude of braking and propulsive forces provides insights into the demands of muscle components [94, 95].

Running at a constant speed, the momentum lost during braking must equal the momentum gained during propulsion [96]. The time the body undergoes braking forces has been shown to be shorter in BR compared to FR at constant speeds [60]. Alternatively, the time generating propulsive forces has been found to be longer during BR than FR [60]. The differences in time during braking and propulsion between BR and FR indicate that the mean force experienced while braking is greater in FR, while the mean force necessary for propulsion is greater during BR [61].

Expanding on the expression of force between BR and FR, Cavagna and colleagues [60, 61] discovered that the propulsive power during BR is, on average, greater than the braking power. Ultimately, the difference between backward and FR is due to a significant increase of the average propulsive power with a non-significant change in average braking power. This information suggests that compared to FR, BR may be less efficient at transferring eccentric energy to concentric energy via the stretch shortening cycle [60, 61], therefore indicating that FR is more reliant on the elastic components of the motor unit, while BR relies more heavily on the contractile component. If increasing contractile potential of lower limb motor-units is an objective, then BR may be a method to enhance these qualities.

3.4.4 Rate of force development. The speed in which the contractile elements of the muscle can develop force i.e. rate of force development [97], is an important determinant of explosive potential across a range of physical performance tasks differing in stretch-shortening cycle durations for both youth and adults [98-101]. Rate of force development during BR has been shown to be approximately 22% greater than FR across speeds ranging from 1.75 m/s to 3.5 m/s and was found to increase more rapidly with speed in BR compared to FR, with the greatest differences being realized at the highest speeds [54]. The translation of these findings in a performance context is that BR is less reliant on the parallel and series elastic components of muscle, and appears to require greater recruitment of the contractile components, particularly at greater running speeds.

PLEASE INSERT Fig 3. Kinetics of backward running compared to forward running [27-29, 38, 43, 60, 91]. The differences shown are relative to forward running. *about here*

GRF = ground reaction force

3.5 Summary

In summary, it seems BR provides a unique energetic and biomechanics profile compared to FR (see Figure 4). When comparing the acute responses, BR shows less efficient step kinematics and stretch-shortening cycle characteristics for producing high running speeds when compared to FR [26, 29, 43, 60, 61, 69]. However, BR appears to display beneficial characteristics related to total muscle activation [36, 80], average muscle force per unit ground force [54], utilization of the contractile element of the motor unit [60, 61], lower knee joint loads [27-29] and higher rate of force development [54] when compared to FR at matched absolute and relative speeds. While this information is promising for rehabilitation and performance purposes, most research has been conducted at relatively slow speeds where BR and FR were matched at absolute velocities. Knowing that maximal BR speed is approximately 30% slower than maximal FR speed [26, 90], further research is needed to conclude whether the available findings can be translated to comparisons at higher, relatively matched running speeds. Furthermore, as external resistance is known to influence biomechanical determinants during FR [21, 53, 102], the acute effects of adding resistance to BR is unknown.

PLEASE INSERT Figure 4. Key characteristics of backward running compared to forward running at relative and absolute speeds [26-29, 36, 43, 54, 57-59, 61, 69, 80]. The differences shown are relative to forward running. *about here*

FR = forward running

4 Longitudinal Responses to Backward Running Training

4.1 Warm-up programs to reduce injury and enhance performance in athletes

An integral purpose of most sports training programs is to prevent injuries and enhance athletic performance. Thus, warm-up protocols which include BR have been developed and researched in adult and youth populations [35, 103]. The most notable programs include the FIFA 11+ [35, 104], FIFA 11+ Kids [34] performance enhancement and injury prevention [48], HarmonKnee [45] and Dynamic Warm-Up programs [105].

From a prevention perspective, these warm-up programs have shown to statistically reduce lower limb overuse and injury prevalence [106]. Additionally, it seems that these programs can significantly enhance quadriceps and hamstring strength [103, 105], hamstring flexibility, [105], sprint performance [31] and dynamic balance [107]. Whilst the authors are aware that the warm-ups comprise of multiple movements and it is difficult to disentangle the contribution of each exercise to the researchers' findings, these results provide support for implementing warm-up programs that includes BR.

4.2 Aerobic and anaerobic adaptations of backward running

Two research teams have examined the longitudinal effects of BR on physical and fitness adaptations [39, 108], although one must be cognizant that neither compared the effects to FR. Terblanche et al. [39] tested the effects of a BR program on physical and performance components of fitness in 26 habitually-trained females. After training BR three times a week for six-weeks, the training group decreased body fat by 2.4% ($p = 0.01$), increased predicted maximal oxygen uptake (VO_{2max}) by 5.2% ($p = 0.01$), improved FR economy by 30.3% ($p = 0.01$) and decreased blood lactate concentration after submaximal FR by -17.1% ($p = 0.01$). The control group, which were not exposed to a training stimulus, did not show significant improvements in any of the tests. These findings provide some evidence that chronic BR can improve both physical and performance components of athletic fitness, however, whether it has any advantage over FR remains unclear.

In a group of highly-trained male runners, Ordway and colleagues [108] quantified the effects of a 5-week BR training program on FR economy. The eight athletes completed two training sessions a week for 5-weeks, which resulted in significant improvements (2.54%; $p = 0.032$) in steady state FR oxygen consumption, i.e. running economy. This finding is of importance because it is comparable to improvements which have been reported after strength, plyometric, and altitude training interventions [109-111]. Contrary to the findings of Terblanche et al. [39], Ordway and colleagues [108] did not find significant changes in VO_{2max} or body composition following BR training. The lack of improvement in VO_{2max} might be a reflection of the characteristics of the athletes, who were ranked above the 80^{th} percentile in VO_{2max} at the pre-test. Something to consider is that the post-test results were compared to the post-familiarized results. While this is good scientific practice, readers must be cognizant that the 5-weeks of familiarization and 5-weeks of training followed the same overload program, differentiated in run training intensity by only 0.45 ms^{-1} and fitness responses may have occurred during the first 5-weeks of familiarization. The above findings support the hypothesis of previous researchers that aerobic capacity could be improved from BR training due to the relatively larger acute energetic costs and cardiopulmonary demands BR places on the body compared to FR [54, 58, 69]. One may argue that increasing the speed of FR to impose higher aerobic and anaerobic demands would be a more specific form of training, however many field and court sports are not unidirectional [112, 113] and athletes may benefit from the reduced knee joint loading [27-29] and increased utilization of shortening muscle actions [54] associated with BR. However, further research is needed to validate such views.

4.3 Strength adaptations of backward running

To the authors' knowledge, only two research teams have published research examining the changes in maximal force production to BR training [38, 114]. Swati et al. [114] examined the effects of BR training on maximal voluntary isometric contraction (MVIC) in a group of males between 18 and 25 years of age. Thirty participants were randomly allocated to either a backward walking (2.48 ms^{-1}), backward running (3.48 ms^{-1}), or a control group. The subjects performed their respective exercise three times a week for six weeks. It was found that the BR group significantly improved MVIC at 60° knee flexion by 10% in relation to the control group. These increases in isometric performance might be indicative of the isometric nature of BR, i.e. heavy reliance on contractile element with smaller range of motion [36]. It should be noted that this study did not include a FR group, therefore direct comparisons between the effectiveness of BR versus FR on strength adaptations cannot be made from these findings.

Threlkeld and colleagues [38] compared the effects of an 8-week BR versus FR training program on the isokinetic muscular torque production (IMTP) in a group of ten adult runners (6 males, 4 females). The runners were assigned to either an 8-week FR or BR training group. The FR group was instructed to continue their normal FR program with no changes, whereas the BR group gradually included BR into their FR program. Subjects were encouraged to set a 10-12 minute per mile pace (2.24 - 2.68 ms^{-1}) during BR. Improvements in knee extensor IMTP were over two times greater in the BR group at 120 degrees per second and over four-fold larger at 75 degrees per second compared to the FR group. Additionally, the BR group showed significant improvements in ankle plantarflexor IMTP at 120 degrees per second, which were nearly ten times greater versus the changes in the FR group. The changes indicate that BR could be a technique for strengthening the quadriceps and plantarflexor muscles. This study is beneficial as it is one of the few to include a FR control group and provide direct insights into the utility of BR training versus FR training.

4.4 Linear speed and change of direction performance

Swati and colleagues [114] measured the effects of BR training on change of direction speed in a group of males aged 18-25 years compared to a backward walking and control group. The researchers found that BR and backward walking training three times a week for 6-weeks significantly improved change of direction performance by 3.86% and 2.38%, respectively, yet no significant changes were found for the control group who were not exposed to any training intervention (-0.66%). Change of direction performance from pre- to post-testing was found to be significantly different for the three aforementioned conditions, with the greatest difference between the BR group and control group ($p = 0.01$). This research highlights the ability of a 6-week BR training program to improve change of direction performance in a group of male university aged subjects. However, this study did not compare the training effects of BR to FR.

One study compared the effects of BR training versus FR training on linear sprint-running and change of direction performance in seventeen highly-trained female athletes [30]. The BR and FR groups followed the same training programme biweekly for six weeks. The running was performed at maximum intensity with work-to-rest ratios between 1:5 and 1:3. Linear sprint-running performance did not differ from pre-training to post-training for the BR group, although the FR group showed declines in performance over 20 m, with significant ($p < 0.05$) decreases of 6.46% and 4.54% over 5 and 10 m, respectively. Change of direction performance for the BR group showed significant improvements for all change of direction tasks, ranging from 2.99% for the 505-agility test to 10.33% in a ladder test. The improvements in the BR group were also found to be significantly greater than the FR group, which showed a range of improvements from 0.38% in the 505-agility test to 2.87% in the ladder test. These findings suggest that BR training may be used to improve change of direction performance and maintain linear forward sprint-running performance.

4.5 Summary

The longitudinal adaptations to BR training appear to be beneficial for improving aerobic and anaerobic performance, isometric and concentric leg strength, and change of direction performance. These adaptations offer valuable insights into the possible applications of BR training in sports training programs.

Studies that have quantified the effects of BR on physical and physiological adaptations are few and typically carry a number of limitations e.g. lack of FR versus BR and/or lack of a training control group. From a practical perspective, this means that coaches and athletes wishing to use BR training do not have support for how to prescribe intensity or load to systematically overload training for their desired adaptations. It is unknown whether BR training is the panacea for injury prevention or performance enhancement. However, if BR is empirically investigated using robust methodological approaches, researchers and coaches may better understand the utility of implementing BR into a sports training program.

5 Practical Application

Repetitive stress on musculoskeletal structures may lead to overuse injuries. Therefore, BR may be a method to increase training variability and reduce injury prevalence. From a performance perspective, exercises such as the start and acceleration phases during sprint running are known to require large isometric and concentric muscular forces. It may be hypothesised that BR could be used as a method to train such movements based on the knowledge that BR requires greater isometric and concentric demands of the musculotendinous structures of the legs to propel the body than constant speed FR at relative speeds. Furthermore, reductions in total lower limb ROM expressed during BR would allow the foot to be repositioned more rapidly and increase stride frequency. Higher stride frequency displayed during BR might help improve the neurophysiological functions of the body to increase maximal FR performance. This is further supported by the fact that greater vertical leg stiffness is associated with BR compared to FR. High vertical leg stiffness is known to be concomitant with greater maximal forward sprinting speed.

6 Conclusion and Research Suggestions

It appears that BR exhibits a unique energetic and biomechanical profile compared to FR. Whilst running speed may be limited by musculoskeletal function during BR, researchers have reported that the acute responses may be beneficial from both clinical and performance perspectives compared to FR. Energetics and biomechanics encompass a large portion of variables important for understanding the demands of a movement, yet only a small number of scientific investigations have researched these determinants in BR.

Empirical support exists for implementing warm-up programs which include BR into sports training programs to both fortify athletes against injury and improve performance. Additional evidence suggests that BR might be a training strategy to improve cardiovascular and neurophysiological functions necessary for optimizing athletic performance. Whilst empirically supported reports are encouraging, longitudinal research on the training effects of BR is scarce. Currently, the training studies conducted on BR have been un-resisted, therefore it is unknown how prolonged loading of BR may affect athletic performance. Additionally, most of these training studies are not designed to analyse the effects on trained athletes. Furthermore, none have analysed the effects on paediatric populations. Without knowledge in these areas, a dearth of scientific insight exists pertaining to BR training.

The biomechanics of BR are relatively well understood at slow running speeds, nevertheless little is known about how these determinants change with relation to running velocity or with various types of external resistance. Given this information, it is suggested that more empirical research should be conducted in this area. The findings of these investigations may allow for a more complete understanding of how BR may be implemented into sports training programs to achieve a desired training effect.

Until now, sports scientists have shown relatively little interest in developing BR training strategies that could improve athletic performance. The lack of research in this area means that coaches must make decisions concerning sport performance training without the support of empirical data. It is our recommendation that future research investigate the influence of speed and resistance on the acute and chronic effects of BR and FR. Additionally, we recommend that explorations be conducted in both youth and adult populations to understand whether BR is influenced by either maturation or training history.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Compliance with Ethical Standards

Funding

No sources of funding were used to assist in the preparation of this article.

Conflicts of Interest

Aaron Uthoff , Jon Oliver, John Cronin, Craig Harrison and Paul Winwood declare that they have no conflicts of interest relevant to the content of this review.

References

1. Cappellini G, Ivanenko YP, Poppele RE, Lacquaniti F. Motor patterns in human walking and running. J Neurophysiol. 2006;95:3426-37.

2. Reilly T, Williams AM, Nevill A, Franks A. A multidisciplinary approach to talent identification in soccer. J Sports Sci. 2000;18:695-702.

3. Gabbet T. Influence of physiological characteristics on selection in a semiprofessional first grade rugby league team: a case study. J Sports Sci. 2002;20(5):399-405.

4. Sierer PS, Battaglini B, Mihalik JP, Shields EW, Tomasini JT. The National Football League Combine: performance differences between drafted and nondrafted players entering the 2004 and 2005 drafts. J Strength Cond Res. 2008;22(1):6-7.

5. Bezodis NE, Trewartha G, Salo AI. Understanding the effect of touchdown distance and ankle joint kinematics on sprint acceleration performance through computer simulation. Sports Biomech. 2015 Jun;14(2):232-45.

6. Anderson T. Biomechanics and running economy. Sports Med. 1996;22(2):76-89.

7. Williams KR. Biomechanical factors contributing to marathon race success. Sports Med. 2007;37(4-5):420-3.

8. Stöggl T, Wunsch T. Biomechanics of Marathon Running. In: Zinner C, Sperlich B, editors. Marathon Running: Physiology, Psychology, Nutrition and Training Aspects. Switzerland: Springer International Publishing; 2016. p. 13-45.

9. Kawamori N, Nosaka K, Newton RU. Relationships between ground reaction impulse and sprint acceleration performance in team sport atheltes. J Strength Cond Res. 2013;27(3):568-73.

10. Mero A, Komi PV, Gregor RJ. Biomechanics of sprint running: a review. Sports Med. 1992;13(6):376-92.

11. Petrakos G, Morin JB, Egan B. Resisted sled sprint training to improve sprint performance: a systematic review. Sports Med. 2016;46(3):381-400.

12. Denadai BS, de Aguiar RA, de Lima LC, Greco CC, Caputo F. Explosive training and heavy weight training are effective for improving running economy in endurance athletes: a systematic review and meta-analysis. Sports Med. 2017;47(3):545-55.

13. Rumpf MC, Lockie RG, Cronin JB, Jalilvand F. The effect of different sprint training methods on sprint performance over various distances: A brief review. J Strength Cond Res. 2016.

14. Støren O, Helgerud J, Støa EM, Hoff J. Maximal strength training improves running economy in distance runners. Med Sci Sports Exerc. 2008;40(6):1087-92.

15. Coh M, Bracic M. Kinematic, dynamic and EMG factors of a sprint start. Track Coach. 2010:6172-6.

16. Hoogkamer W, Kram R, Arellano CJ. How biomechanical improvements in running economy could break the 2-hour marathon barrier. Sports Med. 2017;47(9):1739-50.

17. Folland JP, Allen SJ, Black MI, Handsaker JC, Forrester SE. Running technique is an important component of running economy and performance. Med Sci Sports Exerc. 2017;49(7):1412-23.

18. Debaere S, Jonkers L, Delecluse C. The contribution of step characteristics to sprint running performance in high-level male and female athletes. J Strength Cond Res. 2013;27(1):116-24.

19. Rumpf MC, Cronin JB, Pinder SD, Oliver J, Hughes M. Effect of different training methods on running sprint times in male youth. Ped Exerc Sci. 2012;24:170-86.

20. McMillan K, Helgerud J, Macdonald R, Hoff J. Physiological adaptations to soccer specific endurance training in professional youth soccer players. Br J Sports Med. 2005;39(5):273-7.

21. Cronin J, Hansen K, Kawamori N, McNair P. Effects of weighted vests and sled towing on sprint kinematics. Sports Biomech. 2008;7(2):160-72.

22. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. J Sports Sci. 2003;21:519-28.

23. Hoogkamer W, Meyns P, Duysens J. Steps forward in understanding backward gait: from basic circuits to rehabilitation. Exerc Sports Sci Rev. 2014 Jan;42(1):23-9.

24. Mehdizadeh S, Arshi AR, Davids K. Quantifying coordination and coordination variability in backward versus forward running: Implications for control of motion. Gait Posture. 2015 Jul;42(2):172-7.

25. Jeffreys I. Motor Learning - applications for agility, part 1. Strength Cond J. 2006;28(5):72-6.

26. Arata A. Kinematic and kinetic evaluations of high speed backward running [Dissertation]: University of Oregon; 1999.

27. Sussman DH, Alrowayeh H, Walker ML. Patellofemoral joint compressive forces during backward and foward running at the same speed. J Musculoskelet Res. 2000;4(2):107-18.

28. Roos PE, Barton N, van Deursen RWM. Patellofemoral joint compression forces in backward and forward running. J Biomech. 2012;45:1656-60.

29. Flynn TW, Soutas-Little RW. Patellofemoral joint compressive forces in forward and backward running. J Orthop Sports Phys Ther. 1995 May;21(5):277-82.

30. Terblanche E, Venter RE. The effect of backward training on the speed, agility and power of netball players. S Afr J Res Sport Ph. 2009;31(2):135-45.

31. Ayala F, Calderón-López A, Delgado-Gosálbez JC, Parra-Sánchez S, Pomares-Moguera C, Hernández-Sánchez S, et al. Acute effects of three neuromuscular warm-up strategies on several physical performance measures in football players. PLos ONE. 2017;12(1):e0169660.

32. Magalhães T, Ribeiro F, Pinheiro A, Oliveira J. Warming-up before sporting activity improves knee position sense. Phys Ther Sport. 2010;11(3):86-90.

33. Olsen OE, Myklebust G, Engebretsen L, Holme I, Bahr R. Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. BMJ. 2005;330(7489):449-52.

34. Rössler R, Donath L, Bizzini M, 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. 2016;34(6):549-56.

35. Soligard T, Myklebust G, Steffen K, Holme I, Silvers H, Bizzini M, et al. Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. BMJ. 2008(a2469):1-9.

36. Flynn TW, Soutas-Little RW. Mechanical power and muscle action during forward and backward running. J Orthop Sports Phys Ther. 1993 Feb;17(2):108-12.

37. Mackie JW, Dean TE. Running backward training effects on upper leg musculature and ligamentous instability of injured knees. Med Sci Sports Exerc. 1984;16:151.

38. Threlkeld AJ, Horn TS, Wojtowicz G, Rooney JG, Shapiro R. Kinematics, ground reaction force, and muscle balance produced by backward running. J Orthop Sports Phys Ther. 1989;11(2):56-63.

39. Terblanche E, Page C, Kroff J, Venter RE. The effect of backward locomotion training on the body composition and cardiorespiratory fitness of young women. Int J Sports Med. 2005 Apr;26(3):214-9.

40. Zois J, Bishop D, Aughey R. High-intensity warm-ups: effects during susequent intermittent exercise. Int J Sports Physiol Perform. 2015;10:498-503.

41. Golubitsky M, Stewart I, Buono PL, Collins JJ. Symmetry in locomotor central pattern generators and animal gaits. Nature. 1999;401(6754):693-5.

42. Choi JT, Bastian AJ. Adaptation reveals independent control networks for human walking. Nat Neurosci. 2007;10:1055-62.

43. Weyand PG, Sandell RF, Prime DN, Bundle MW. The biological limits to running speed are imposed from the ground up. J Appl Physiol. 2010 Apr;108(4):950-61.

44. Morton C. Running backward may help athletes move forward. Phys Sports Med. 1986;14:149-52.

45. Kiani A, Hellquist E, Ahlqvist K, Gedeborg R, Michaélsson K, Byberg L. Prevention of soccer-related knee injuries in teenaged girls. Arch Intern Med. 2010;170:43-9.

46. Heiderscheit BC, Sherry MA, Silder A, Chumanov ES, Thelen DG. Hamstring strain injuries: recommendations for diagnosis, rehabilitation, and injury prevention. J Orthop Sports Phys Ther. 2010;40(2):67-81.

47. Mattacola CG, Dwyer MK. Rehabilitation of the ankle after acute sprain or chronic instability. J Athl Train. 2002;37(4):413-29.

48. Gilchrist J, Mandelbaum BR, Melancon H, Ryan GW, Silvers HJ, Griffin LY, et al. A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. Am J Sports Med. 2008;36:1476-83.

49. Mann RA, Hagy J. Biomechanics of walking, running, and sprinting. Am J Sports Med. 1980;8(5):345-50.

50. Brughelli M, Cronin J, Chaouachi A. Efffects of running velocity on running kinetics and kinematics. J Strength Cond Res. 2011;25(4):933-9.

51. van Oeveren BT, de Ruiter CJ, Beek PJ, van Dieën JH. Optimal stride frequencies in running at different speeds. PLoS ONE. 2017;12(10):e0184273.

52. Arampatzis A, Bruggemann GP, Metzler V. The effect of speed on leg stiffness and joint kinetics in human running. J Biomech. 1999;32(12):1349-53.

53. Alcaraz PE, Palao JM, Elvira JLL, Linthrone NP. Effects of three types of resisted sprint training devices on the kinematics os sprinting at maximum velocity. J Strength Cond Res. 2008;22(3):890-7.

54. Wright S, Weyand PG. The application of ground force explains the energetic cost of running backward and forward. J Exper Biol. 2001;204:1805-15.

55. Kram R, Taylor R. Energetics of running: a new perspective. Nature. 1990;346(6281):265-7.

56. Minetti AE, Alexander RM. A theory of metabolic costs for bipedal gaits. J Theor Biol. 1997;186(4):467-76.

57. Adesola AM, Azeez OM. Comparison of cardio-pulmonary responses to forward and backward walking and runnin. Afr J Biomed Res. 2009;12(2):95-100.

58. Flynn TW, Connery SM, Smutok MA, Zeballos RJ, Weisman IM. Comparison of cardiopulmonary responses to forward and backward walking and running. Med Sci Sports Exerc. 1994 Jan;26(1):89-94.

59. Conti CA. The mechanical determinats of energetic cost in backward running: Humboldt State University; 2009.

60. Cavagna GA, Legramandi MA, La Torre A. Running backwards: soft landing-hard takeoff, a less efficient rebound. Proc Biol Sci. 2011 Feb 7;278(1704):339-46.

61. Cavagna GA, Legramandi MA, La Torre A. An analysis of the rebound of the body in backward human running. J Exp Biol. 2012 Jan 1;215(Pt 1):75-84.

62. Herzog W, Leonard TR, Joumaa V, Mehta A. Mysteries of muscle contraction. J Appl Biomech. 2008;24(1):1-13.

63. Lindstedt SL, LaStayo PC, Reich TE. When active muscles lengthen: properties and consequences of eccentric actions. News Physiol Sci. 2001;16:256-61.

64. Heglund NC, Taylor CR. Speed, stride frequency and energy cost per stride: how do they change with body size and gait? J Exp Biol. 1988;138:301-18.

65. Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin NA, Duchateau J. Rate of force development: physiological and methodological considerations. Eur J Appl Physiol. 2016;116(6):1091-116.

66. Moir GL. Strength and Conditioning: A Biomechanical Approach. Burlington, MA: Jones & Bartlett Learning; 2015.

67. Napier C, Cochrane CK, Taunton JE, Hunt MA. Gait modifications to change lower extremity gait biomechanics in runners: a systematic review. Br J Sports Med. 2015 Nov;49(21):1382-8.

68. Novacheck TM. The biomechanics of running. Gait Posture 1998;7:77-95.

69. DeVita P, Stribling J. Lower extremity joint kinetics and energetics during backward running. Med Sci Sports Exerc. 1991 May;23(5):602-10.

70. Hansen AH, Childress DS, Miff SC, Gard SA, Mesplay KP. The human ankle during walking: implications for design of biomimetic ankle protheses. J Biomech. 2004;37:1467-74.

71. Bates BT, Morrison E, Hamill J. A comparison between forward and backward running. In: Adrian M, Deutsch H, editors. The 1984 Olympic Scientific Congress Proceedings: Biomechanics; 1984; Eugene, Oregon: Microform publications; 1984. p. 127-35.

72. Butler RJ, Corwell III HP, Davis IM. Lower extremity stiffness: implications for performance and injury. Clin Biomech. 2003;18:511-7.

73. Hoy MG, Zajac FE, Gordon ME. A musculoskeletal model of the human lower extremity: the effect of muscle, tendon, and moment arm on the moment-angle relationship of musculotendon actuators at teh hip, knee and ankle. J Biomech. 1990;23(2):157-69.

74. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation on joint mechanics during running. Med Sci Sports Exerc. 2011;43(2):296-302.

75. Guo L, Su F, Yang C, Wang S, Chang J, Wu W, et al. Effects of speed and incline on lower extremity kinemtics during treadmill jogging in healthy subjects. Biomed Eng Appl Basis Communs. 2006;18(2):73-9.

76. Gajer B, Thépaut-Mathieu C, Lehénaff D. Evolution of stride and amplitude during course fo the 100m event in athletics. New Stud Athlet. 1999;14:43-50.

77. Hunter JP, Marshall RN, McNair PJ. Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. J Appl Biomech. 2005;21:31-43.

78. Mann R, Herman J. Kinematic analysis of Olympic sprint performance, Men's 200 meters. Int J Sports Biomech. 1985;1:151-62.

79. Morin JB, Bourdin M, Edouard P, Peyrot N, Samozino P, Lacour JR. Mechanical determinants of 100-m sprint running performance. Eur J Appl Physiol. 2012 Nov;112(11):3921-30.

80. Sterzing T, Frommhold C, Rosenbaum D. In-shoe plantar pressure distribution and lower extremity muscle activity patterns of backward compared to forward running on a treadmill. Gait Posture. 2016 May;46:135-41.

81. Komi PV, Gollhofer A, Schmidtbleicher D, Frick U. Interaction between man and shoe in running: considerations for a more comprehensive measurement approach. Int J Sports Med. 1987;8(3):196-202.

82. Dietz V. Human neuronal control of automatic functional movements. Interaction between central programs and afferent input. Physiol Rev. 1992;72:33-69.

83. Duysens J, Tax AA, Murrer L, Dietz V. Backward and forward walking use different patterns of phase-dependent modulation of cutaneous reflexes in humans. J Neurophysiol. 1996 Jul;76(1):301-10.

84. Grasso R, Bianci L, Lacquaniti F. Motor patterns for human gait: backward versus forward locomotion. J Neurophysiol. 1998;80(4):1868-85.

85. Winter DA, Pluck N, Yang JF. Backward walking: a simple reversal of forward walking? J Motor Behav. 1989;21:291-305.

86. Bramble DM, Lierberman DE. Endurance running and the evolution of *Homo*. Nature. 2004;432:345-52.

87. Mattson MP. Evolutionary aspects of human exercise - born to run purposefully. Ageing Res Rev. 2012;11(3):347-52.

88. Joshi S, Vij JS, Singh SK. Medical science retrowalking: a new concept in physiotherapy and rehabilitation. Int J Sci Res. 2015;4(10):152-6.

89. Nourbakhsh MR, Kukulka CG. Relationship between muscle length and moment arm on EMG activity of human triceps surae muscle. J Electromyogr Kinesiol. 2004;14(2):263-73.

90. Weyand PG, Sternlight DB, Bellizzi MJ, Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. J Appl Physiol. 2000;81:1991-9.

91. Curtiss C, Orloff H, Usagawa T. Analysis of round reaction forces produced in basketball maneuvers over a season. XXIV International Symposium on Biomechanics in Sports; 2006 16 July; Salzburg, Austria; 2006.

92. McNeill AR. The human machine. New York: Columbia University Press; 1992.

93. Derrick TR, Hamill J, Caldwell GE. Energy absorption of impacts during running at various stride lengths. Med Sci Sports Exerc. 1998;30(1):128-35.

94. Ellis RG, Sumner BJ, Kram R. Muscle contributions to propulsion an dbraking during walking and running: insights from external force perturbations. Gait Posture. 2014;40(4):594-9.

95. Hamner SR, Seth A, Delp SL. Muscle contributions to propulsion and support during running. J Biomech. 2010;43(14):2709-16.

96. Cavagna GA, Legramandi MA, Peyre-Tartaruga LA. The landing-takeoff asymmetry of human running is enhanced in old age. J Exp Biol. 2008;211(pt10):1571-8.

97. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeleton muscle following resistance training. J Appl Physiol. 2002;93(4):1318-26.

98. Laffaye G, Wagner PP, Tombleson TI. Countermovement jump height: gender and sport-specific differences in force-time variables. J Strength Cond Res. 2014;28(4):1086-105.

99. Slawinski J, Bonnefoy A, Levêque JM, Ontanon G, Riquet A, Dumas R, et al. Kinematic and kinetic comparisons of elite and well-trained sprinters during sprint start. J Strength Cond Res. 2010;24(4):896-905.

100. Gissis I, Papadopoulos C, Kalapotharakos VI, Sotiropoulos A, Komsis G, Manolopoulos E. Strength and speed characteristics of elite, subelite, and recreational young soccer players. Res Sports Med. 2006;14:205-14.

101. Nuzzo JL, McBride JM, Cormie P, McCaulley GO. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. J Strength Cond Res. 2008;22(3):699-707.

102. Lockie RG, Murphy A, Spinks CD. Effects of resisted sled towing on sprint kinematics in field-sport athletes. J Strength Cond Res. 2003;17(4):760-7.

103. Daneshjoo A, Mokhtar A, H, Rahnama N, Yusof A. Effectiveness of injury prevention programs on developing quadriceps and hamstrings strength of young male professional soccer players. J Hum Kinet. 2013;39:115-25.

104. Longo UG, Loppini M, Berton A, Marinozzi A, Maffulli N, 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. 2012;40(5):96-1005.

105. Aguilar AJ, DiStefano LJ, Brown CN, Herman DC, Guskiewicz KM, Padua DA. A dynamic warm-up model increases quadriceps strength and hamstring flexibility. J Strength Cond Res. 2012;26(4):1130-41.

106. Herman K, Barton C, Malliaras P, Morrissey D. The effectiveness of neuromuscular warm-up strategies, that require no additional equipment, for preventing lower limb injuries during sports participation: a systematic review. BMC Med. 2012;10(75):1-12.

107. Daneshjoo A, Mokhtar A, H, Rashnama N, Yusof A. The effects of comprehensive warm-up programs on proprioception, static and dynamic balance on male soccer players. PLos ONE. 2012;7(12):e51568.

108. Ordway JD, Laubach LL, Vanderburgh PM, Jackson KJ. The effects of backwards running training on forward running economy in trained males. J Strength Cond Res. 2016;30(3):763-7.

109. Millet GP, Jaouen B, Borrani F, Candau R. Effects of concurrent endurance and strength training on running economy and VO(2) kinetics. Med Sci Sports Exerc. 2002;34(8):1351-9.

110. Saunders PU, Telford RD, Pyne DD, Hahn AG. Improved race performance in elite middle-distance runners after cumulative altitude exposure. Int J Sports Physiol Perform. 2009;4(1):134-8.

111. Saunders PU, Telford RD, Pyne DB, Peltola EM, Cunningham RB, Gore CJ, et al. Short-term plyometric training improves running economy in highly trained middle and long distance runners. J Strength Cond Res. 2006;20(4):947-54.

112. Jones P, Bampouras T, Marrin K. An investigation into the physical determinants of change of direction speed. J Sports Med Phys Fitness. 2009;49(1):97-104.

113. Gabbett TJ, Kelly JN, Sheppard JM. Speed, change of direction speed, and reactive agility of rugby league players. J Strength Cond Res. 2008;22(1):174-81.

114. Swati K, Ashima C, Saurabh S. Efficacy of backward training on agility and quadriceps strength. Elixir Hum Physiol. 2012;53:11918-21.