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SYSTEMATIC REVIEW

Physiological and Biomechanical Responses to Running on Lower Body Positive Pressure Treadmills in Healthy Populations

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Abstract

Background Lower body positive pressure treadmills (LBPPTs) aim to reduce musculoskeletal loading during running. As LBPPTs have become more commercially available, they have become integrated into athletic performance and clinical rehabilitation settings. Consequentially, published research examining the biomechanical and physiological responses to unweighted running has increased.

Objective The purpose of this systematic review was to synthesize the literature in an attempt to provide researchers and clinicians with a comprehensive review of physiologic and biomechanical responses to LBPPT running.

Methods Through a generic search of PubMed, CINAHL, MEDLINE, and SPORTDiscus using a comprehensive list of search terms related to LBPPT, unweighting, and body weight support during running, we identified all peer-reviewed publications that included LBPPT running. Two reviewers independently evaluated the quality of studies using a modified Downs and Black checklist for non-randomized studies.

Results A total of 15 articles met the inclusion criteria for this review. Peak and active vertical ground-reaction forces were consistently reduced with unweighting, but regional loading within the foot was also altered towards a forefoot strike. LBPPTs also provide some horizontal assistance. Neuromuscular activation is generally reduced with LBPPTs, but the stabilizer muscle groups may respond differently than the propulsive muscle groups. Submaximal heart rate and volume oxygen consumption are reduced with unweighting, but physiologic response remains generally unchanged at maximal intensities.

Conclusions The current literature suggests that LBPPTs are effective in allowing individuals to achieve a given metabolic stimulus with reduced musculoskeletal loading. However, LBPPTs not only reduce impact but also change neuromuscular activation and biomechanics in a complex manner. Thus, clinicians must account for the specific biomechanical and physiological alterations induced by LBPPTs when designing training programs and rehabilitation protocols.

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Key Points

Lower body positive pressure treadmills (LBPPTs), such as the AlterG, are effective for reducing impact during running.

To achieve an aerobic intensity similar to that of normal treadmill running, faster speeds must be used when performing reduced-impact training on an LBPPT.

The magnitude of biomechanical and physiological alterations appears to become more exaggerated at body weight settings <70 %; thus, individuals looking to train while receiving the benefits of unweighting while minimizing changes in running mechanics are encouraged to stay above this threshold.

Although LBPPTs reduce impact during running, mechanics and muscle activation pattern changes are complex.

1 Introduction

Running may be viewed as a healthy activity because it ultimately provides cardiometabolic benefits, but lower extremity musculoskeletal overuse injuries are very common in runners at various competitive levels [1, 2]. Epidemiological data also demonstrate that running is the most frequent cause of exercise- and sport-related injuries in the military [3]. Likewise, there is a high incidence of overuse injuries in recreational athletes, with around 10 % of novice runners reporting injury within a 6-week supervised training program [4]. These injuries ultimately lead to decreased training, with a median recovery time of 71 days reported in one study focused on novice runners [5]. Some specific injuries, such as stress fractures, are associated with particularly significant morbidity [6], and one study reported that nearly 5 % of injured novice runners underwent surgical treatment [5]. Further, numerous studies have demonstrated that the main risk factor for running injuries is a previous history of other running injuries [7–9]. This suggests that some running injuries may not necessarily be new injuries, but rather re-occurrences of previous injuries that were not fully healed.

Given the high prevalence of running injuries, there is great interest in researching interventions that may decrease the risk of injury and improve rehabilitation of existing injury. One common approach to achieve this has been through reducing musculoskeletal loading. Recent prospective evidence indicates that biomechanical variables related to impact are lower in runners who have not sustained musculoskeletal injuries, and this supports data from numerous retrospective studies that have demonstrated greater loading parameters in injured runners [10]. In the past decade, lower body positive pressure treadmills (LBPPTs) have emerged as a novel tool to reduce loading on the musculoskeletal system during walking and running. Originally, LBPPTs were one of many technological approaches used to simulate the microgravity environment experienced by astronauts [11]. However, unweighted running provides a novel form of exercise training for athletes and may also be highly beneficial in the rehabilitation of clinical populations. Case reports and pilot studies suggest LBPPTs can be utilized in return-to-play programs for individuals with various musculoskeletal injuries [12–14]. Additionally, LBPPTs are often used as training tools to allow for more training with decreased ground-reaction forces and for training at faster than normal paces [15].

Commercially available LBPPTs are now found in various healthcare and sports performance settings, which allows greater accessibility to patient and athletic populations. The devices have a simple interface, such that the user adjusts settings on the treadmill's control panel to select a desired percentage of body weight at which to run. The LBPPT then applies an upward force on the user by increasing the air pressure inside the chamber [16]. In this way, LBPPTs can enable users to run with decreased downward forces acting on their musculoskeletal system. Although no clinical trials to determine the efficacy of LBPPTs in preventing or rehabilitating running injuries are currently available, a wealth of published research articles have reported the biomechanical and physiological effects of unweighted running on LBPPTs. However, direct comparisons between studies are complicated by differences in sample populations and running protocols. As research in this field has been rapidly developing, the literature in this realm has not yet been collectively evaluated to provide clinicians with a more comprehensive understanding of how the LBPPT influences running. Thus, we performed a systematic review to synthesize the literature in an attempt to provide researchers and clinicians with a comprehensive review of physiologic and biomechanical responses to LBPPT running. The synthesis of information provided through this systematic review can provide valuable insight for developing individualized training and rehabilitation programs utilizing an LBPPT, and for the design of clinical trials to determine the clinical efficacy of LBPPTs for preventing and rehabilitation of musculoskeletal injuries.

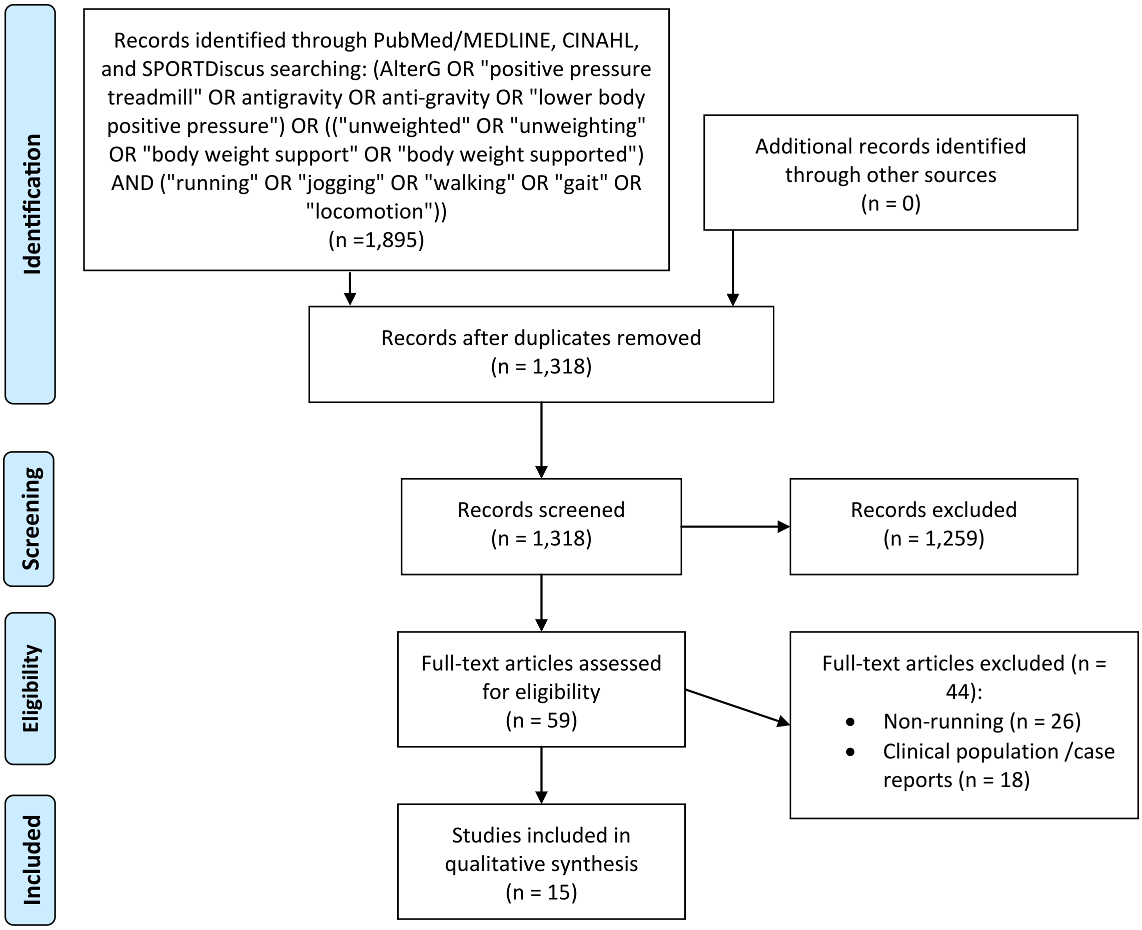

Fig. 1 PRISMA diagram of search strategy

2 Methods

This systematic review was conducted and reported according to the protocol outline by PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [17].

2.1 Identification and Selection of the Literature

To comprehensively identify all peer-reviewed publications that utilized an LBPPT, we used a generic search strategy using PubMed, CINAHL, MEDLINE, and SPORTDiscus databases through 12 June 2015 (Fig. 1). References from each of the articles selected for inclusion were also searched to ensure that all possible articles regarding LBPPTs were accounted for.

2.2 Selection Criteria

An article was eligible for inclusion if it met all of the following criteria: (1) Outcome measures included at least one physiologic or biomechanical response to running on an LBPPT; (2) Article was original research (i.e., not a case study or case series); (3) Article was available as full text (i.e., not a poster or abstract); (4) Article was written in English. An article was excluded if the study population consisted of (1) clinical patients (e.g., individuals with neurologic disease, patients with osteoarthritis) or (2) any population that would have different physiological or biomechanical responses compared with a healthy, active population (e.g., individuals with advanced age, individuals with prosthetic limbs).

2.3 Quality Assessment

Two reviewers independently evaluated the quality of the included studies using a modified version of the Downs and Black checklist for non-randomized studies [18]. Specifically, 11 items of the original checklist were excluded as they were not applicable to the selected studies. Thus, articles had a maximum possible score of 16 points, which evaluated reporting (eight items), external validity (one item), internal validity bias (five items), and internal validity confounding (selection bias) (two items). Reviewers discussed any disagreements until they reached agreement.

2.4 Data Extraction

Two reviewers (KAF, JMS) extracted information and data concerning the study population and subject demographics, design, and results and major findings. The main data extracted included physiological parameters (heart rate [HR], ventilation, and volume of oxygen consumption [$\dot{V}O_2$]) and biomechanical parameters (ground-reaction forces and impact-related variables, stride characteristics, and muscular activation). To minimize confusion for the reader, we have used consistent terminology throughout this paper and propose this nomenclature be used in future research regarding LBPPTs (Table 1).

2.5 Statistical Analysis of Volume of Oxygen Consumption ($\dot{V}O_2$) Response

We determined that $\dot{V}O_2$ was the only variable that was consistently measured and reported across multiple studies to allow for a pooled quantitative analysis. We developed a generalized estimating equation model with autoregressive covariance structure to determine the relationship between $\dot{V}O_2$ (dependent variable), running speed, and unweighting (percent body weight) on an LBPPT. Running speed and unweighting were modeled as within-subject continuous variables (main effects), and study was used as a subject variable. We then used linear regression to compare the predicted values with observed values across studies.

3 Results

A total of 15 studies met inclusion for systematic review (Fig. 1). Table 2 shows the sample population, study design, and summary of general findings. See Table S1 in the electronic supplementary material (ESM) for the risk of bias/quality assessment scores for each study. Only nine of the 15 studies achieved a quality assessment score >50 % (≥9 of 16 criteria).

3.1 Biomechanical Variables

3.1.1 Kinetic Parameters

Six studies [15, 16, 19–22] met the inclusion criteria for this review and addressed kinetic parameters; each reported decreases in peak ground-reaction force with a lower body weight setting (BW_{Set}). Additionally, two studies [15, 20] consistently found that the magnitude of active peak decreased below that of impact peak at lower BW_{Set}, although one additional study demonstrated this through a figure [21], and another demonstrated that mean ground-reaction forces decreased [16]. Only two studies [15, 20] described horizontal forces, and both reported disproportionate decreases in propulsive impulse compared with braking impulse.

Two studies [15, 20] examined the effects of reloading at 100 % BW_{Set} following previous unweighting. Sainton et al. [20] also reported that impact peak and loading rate decreased during reloading at 100 % BW_{Set} following prior unweighted running. Grabowski and Kram [15] reported no significant changes in kinetics at 100 % BW_{Set} following an unloading protocol. A summary of the kinetic parameter findings from each study is presented in Table 3.

3.1.2 Kinematic Parameters

Two studies [19, 20] reported kinematic data. Sainton et al. [20] found that vertical displacement during the brake phase was reduced significantly at 60 and 80 % BW_{Set}. Cutuk et al. [19] found that unweighting on an LBPPT did not significantly change knee or ankle range of motion during running; however, they did observe some non-significant trends.

Table 1 Terminology used for lower body positive pressure treadmill research

Term	Abbreviation	Description
Body weight	BW	An individual's body weight, as measured on earth under standard gravity conditions, reported in newtons (N)
Body weight setting	BW_{Set}	The setting used on the LBPPT control panel used to achieve a desired simulated body weight. This is typically measured in percentage of body weight (e.g., control panel is adjusted to 50 % BW_{Set})
Simulated body weight	BW_{Sim}	The actual measured body weight achieved through positive pressure inflating the capsule surrounding the treadmill
		For example, in the case of a 70-kg person weighing 686.7 N (70 kg × 9.81 m/s^2), if the LBPPT control panel is adjusted to 50 % BW_{Set}, a scale placed under that person inside LBPPT should theoretically indicate a weight of 343.4 N (50 % of 686.7 N) during static conditions

LBPPT lower body positive pressure treadmill

Table 2 Summary of published studies examining biomechanical and physiological responses to lower body positive pressure treadmill running in healthy individuals

Study	LBPPT type	Sample (characteristics[a])	Protocol	Summary of findings
Cutuk et al. [19]	Custom LBPP chamber with Model Q65, Quinten Instruments, Seattle, WA, USA	6 healthy volunteers (22–42 y; 76.2–108.4 kg; 1.78–1.92 m)	Subjects walked at 3 mph and ran at 6 mph at each of the three BW_{Set} (20, 60, and 100 %). ROM of the ankle and knee were analyzed	HR decreased when in LBPPT. Decreased peak vertical GRF, and increased stride length during unweighted running. (Note, most comparisons were between walking and running, rather than between BW_{Set} during running)
Gojanovic et al. [23]	AlterG P200, AlterG, Fremont, CA, USA	14 trained runners (9 M) (27 ± 5 y; 10-km race time 38.1 ± 1.1 min)	Incremental treadmill test on control treadmill (Woodway Pro Series) to measure $\dot{V}O_{2max}$ and HR_{max}. Then, identical test performed on LBPPT at 100, 95, 90, and 85 % BW_{Set} (randomized order, separated by 48 h)	$\dot{V}O_{2max}$ and HR_{max} similar on LBPPT vs. control treadmill across all conditions except HR_{max} at 85 % BW_{Set} (M) and 100 and 90 % BW_{Set} (F) were lower than control treadmill. Lactate similar across all conditions except lower at 85 % BW_{Set} (M)
Gojanovic et al. [31]	AlterG P200	11 healthy M competitive runners or triathletes (35 ± 8 y, $\dot{V}O_{2max}$ 55.7 ± 6.4 ml/kg/min)	Subjects were randomized to LBPPT or control treadmill (Woodway Pro Series) group. They performed 8 sessions over 4 weeks (2 sessions per week) of HIIT on respective treadmill. They completed 4–5 intervals at $v\dot{V}O_{2max}$ for duration equal to 60 % of time to exhaustion at 90 % BW_{Set} (LBPPT group) or without unweighting (control treadmill group)	$v\dot{V}O_{2max}$ increased in both groups but more significantly in LBPPT. Time to exhaustion improved only in LBPPT. Interval training speed and duration was greater in LBPPT, which elicited higher total time spent at $v\dot{V}O_{2max}$ in LBPPT
Grabowski and Kram [15]	G-Trainer (AlterG)	10 volunteers: 7 M, 3 F (64.4 ± 7.4 kg)	Subjects ran at 3.0 m/s at 100 % BW_{Set} before and after running 13 trials (randomized order) at various speeds (3.0, 4.0, and 5.0 m/s) and BW_{Set} (25, 50, 75 %)	Increased peak GRF, active peak GRF, and loading rate with greater BW_{Set}. Longer contact times occurred at 100 % BW_{Set} following unweighting. Combinations of speed and unweighting allowed for equivalent metabolic workload with reduced active peak GRF
Hoffman and Donaghe [22]	AlterG P200	12 healthy subjects: 6 M, 6 F (21–59 y)	Submaximal graded exercise test on three occasions at 100, 75, 50 % BW_{Set}. Four 4-min walking stages and then as many 4-min running stages (1.79, 2.59, 3.49 m/s) as required to get RPE of 13	For running, slopes of speed vs. $\dot{V}O_2$ differed by BW_{Set}. Increases in BW_{Set} resulted in decreases in $\dot{V}O_2$ within a given speed. GRF decreased and maximum loading rate increased for a given $\dot{V}O_2$. BW_{Set} did not affect RPE for a given $\dot{V}O_2$
Hunter et al. [24]	AlterG P200	11 NCAA D1 M cross-country runners (21.2 ± 2.1 y)	EMG was recorded from 12 muscles while subjects ran at 40, 60, 80, and 100 % BW_{Set} for 2 min in random order and linear regression was used to evaluate trends in muscle activation amplitude with unweighting	Most muscles demonstrated lower EMG amplitudes as BW_{Set} was increased. Muscles involved in support of body were significantly less activated during unweighting. Trends were not significant in hip adductors during swing phase and medial/lateral hamstrings during stance phase
Kline et al. [27]	AlterG P200	20 recreational runners: 11 M, 9 F (28.5 ± 8.8 y)	5 sessions of treadmill running: (1) First two sessions of familiarization with LBPPT. Subjects ran for 30 min at self-selected speed—first 5 min at 100 % BW_{Set} and decreased 10 % every 5 min until 50 % BW_{Set} for last 5 min; (2) Third session was on control treadmill (Woodway) and consisted of running multiple 3-min stages with increasing speed (4–7 mph); (3) Fourth and fifth sessions on LBPPT at BW_{Set} 50, 60, 70, 80, 90, and 100 % split across two sessions. Three stages were performed at four different speeds (speeds determined from third session results)	As BW_{Set} decreased, metabolic cost decreased. The proportion of metabolic demand to body weight was found to be roughly equivalent for 70–90 % BW_{Set} but at high and low ends, proportion metabolic demand was significantly different from proportion body weight. A conversion table between BW_{Set} and speed to achieve metabolic equivalent of non-unweighted running was developed
Liebenberg et al. [25]	AlterG P200	9 free from injury and physically active subjects: 5 M, 4 F (24 ± 2 y)	Subjects ran at 100, 115, and 125 % of preferred speed at 100, 90, 80, 70, and 60 % BW_{Set} for a total of 15 running conditions. Condition order was always slow to fast and high to low BW_{Set}. Total duration for each condition was between 1 and 1.5 min	Reducing BW_{Set} led to reduction in muscle activity (i.e., EMG amplitude) with no changes in muscle activation patterns. Increased speed within a BW_{Set} increased muscle activity without changing muscle activation patterns

Table 2 continued

Study	LBPPT type	Sample (characteristics[a])	Protocol	Summary of findings
McNeill et al. [28]	AlterG P200	8 (5 M, 3 F) recreational runners with treadmill, but not LBPPT running experience (23.6 ± 5.4 y)	Subjects ran 15-min trials (5 min at 50, 70, and 90 % BW_{Set}) on AlterG pm 7 separate days, separated by at least 2 days each. Pace was 70–80 % of their velocity measured at $\dot{V}O_{2max}$	$\dot{V}O_2$ was decreased at 50 % BW_{Set} (∼20 % reduction), 70 % BW_{Set} (∼13 % reduction), and 90 % BW_{Set} (∼11 % reduction). An accommodation effect of running on LBPPT was reached after 60 min of accumulated running on LBPPT (four trials of 15 min on separate days)
McNeill et al. [29]	AlterG P200	6 professional elite M long-distance runners (26.4 ± 4 y, 5-km PR <14 min or similar ability)	Subjects ran three 16-min tests consisting of four stages of 4 min at 8, 7, 6, and 5 min/mile pace. One test was run on a control treadmill (Woodway ELG), the other on LBPPT, at 60 % BW_{Set}, and one at 80 % BW_{Set}	Significant decreases in $\dot{V}O_2$ with increases in body weight support. The slope of the relationship between $\dot{V}O_2$ and velocity was steeper with less support. There was more variability in $\dot{V}O_2$ between runners on LBPPT vs. control treadmill
Mercer et al. [26]	AlterG P200	7 healthy subjects: 5 M, 2 F (35.7 ± 10.6 y)	Subjects completed 15 running conditions manipulating speed and BW_{Set}. At each BW_{Set} (100, 50, 40, 30, 20 %), subjects ran at three speeds (100, 11, and 125 % of preferred speed) with condition order always from high to low BW_{Set} and running speed from slow to fast. Subjects ran about 1.5–2 min per condition with treadmill stopped between each condition for rest	Muscle activity increased with speed and decreased with reductions in BW_{Set}
Raffalt et al. [16]	AlterG P200	12 Danish international elite and sub-elite level runners (27.8 ± 3.3 y)	On days 1 and 2, subjects performed $\dot{V}O_{2max}$ test on both control treadmill (Treadmill Opima 807) and LBPPT (separate days, randomized order). Subjects ran 17–20 km/h (10.5–12.5 mph). On day 3, subjects ran three 12-min steady state submaximal trials at 10, 14, 18 km/h separated by 4- to 6-min rest in randomized order. Each trial subdivided into four 3-min bouts, running at 100, 75, 50, 25 % BW_{Set}. After 8-min rest, four trials of two 20-s running at 20 and 22 km/h with randomized order of BW_{Set}	Time to exhaustion 34.5 % longer on LBPPT. $\dot{V}O_2$, ventilation, and HR decreased linearly with increasing BW support. $\dot{V}O_2$max can be achieved on LBPTT at 100 %
Ruckstuhl et al. [30]	Custom LBPP chamber with Quinten Q6500 treadmill	10 recreationally active volunteers: 5 M, 5 F (23 ± 3 y)	$\dot{V}O_2$, HR, and RPE measured at 100, 66, and 33 % BW_{Set} at two treadmill running speeds (2.2 and 3.1 m/s) for 5 min each	All parameters decreased during unweighting. Unweighting had a greater effect at faster running speed. No differences between M and F
Sainton et al. [20]	AlterG M310	7 volunteers: bilateral rear foot-strike runners (21.7 ± 3.6 y)	Two series of 9-min running bouts including 3 min at each condition of 100 % BW_{Set}, either 60 or 80 % BW_{Set}, and then 100 % BW_{Set} again	Unweighted running resulted in lower step frequency (increased flight time), lower impact and active force peaks, and reduced loading rate and push off impulse. Amplitude of muscle activity decreased in some muscles, but this varied between 60 and 80 % BW_{Set}
Smoliga et al. [21]	AlterG P200	10 experienced runners: current or former intercollegiate track athletes (25.2 ± 5.6 y)	Subjects were equipped with pressure insoles and ran at three different speeds (100, 120, and 140 % of each individual's self-reported pace during "easy" training run) and five different BW_{Set} (20, 40, 60, 80, 100 %). Running speed and BW_{Set} randomized within each speed	Maximum in-shoe force and impulse decreased with unweighting. LBPPT caused shift toward forefoot loading, most evident at <80 % BW_{Set}

BW_{Set} body weight setting, *D1* division one, *EMG* electromyography, *F* female, *GRF* ground-reaction force, *HIIT* high-intensity interval training, *HR* heart rate, *HR_{max}* maximum heart rate, *LBPPT* lower body positive pressure treadmill, *M* male, *NCAA* National Collegiate Athletic Association, *PR* personal record, *ROM* range of motion, *RPE* rating of perceived exertion, *SD* standard deviation, *$\dot{V}O_{2max}$* maximum volume of oxygen consumption, *v $\dot{V}O_{2max}$* velocity at $\dot{V}O_{2max}$

[a] Age, weight, height and other characteristics are presented as mean ± SD or range

Table 3 Influence of lower body positive pressure treadmill unweighting on kinetic parameters during running

Study	Peak vGRF		Maximum loading rate	Vertical displacement	Impulse		Notes
	Impact peak vGRF	Active peak vGRF			Braking impulse	Push-off impulse	
Cutuk et al. [19]	↓						
Grabowski and Kram [15]	↓	↓	↓				Impact peak unchanged after reloading. Reported horizontal breaking impulses were greater than propulsive impulses across speeds, but comparisons between BW_{Set} not reported
Hoffman and Donaghe [22]	↓		↔				
Raffalt et al. [16]	↓	↓[a]					Mean vGRF[a]
Sainton et al. [20]	↓	↓	↓	↓	↓ 60 %	↓	Impact peak vGRF and maximum loading rate were decreased after reloading
Smoliga et al. [21]	↓[b]				↓		Peak force quantified, decreased impact vGRF and active vGRF peaks visually reported[b]

BW_{Set} body weight setting, *LBPPT* lower body positive pressure treadmill

[a] Active peak vertical ground-reaction force

[b] Impact peak vertical ground-reaction force

↓ and ↔ indicate decrease and no change, respectively

3.1.3 Stride Characteristics

Five studies [15, 16, 19, 20, 23] met the inclusion criteria for discussion of stride characteristics, but the findings were conflicting. Gojanovic et al. [23] reported stride rate increased in males and remained unchanged in females, whereas Grabowski and Kram [15], Raffalt et al. [16], and Sainton et al. [20] reported decreased stride frequency with unweighting. Grabowski and Kram [15] reported increased contact time, whereas Raffalt et al. [16] reported decreased contact time, and Sainton et al. [20] reported no changes in contact time. Raffalt et al. [16] and Sainton et al. [20] were in agreement that flight duration increased.

Two studies examined the effects of reloading at 100 % BW_{Set} following previous unweighting. Sainton et al. [20] found flight time increased and step frequency decreased during reloading at BW_{Set} 100 % following unweighted running. Grabowski and Kram [15] found contact time, but not stride frequency, at 100 % BW_{Set} was increased following the entire unweighting protocol.

A summary of the stride characteristics findings from each study is presented in Table 4.

3.2 Neuromuscular Activation

Four studies [20, 24–26] met inclusion criteria that were used to evaluate muscle activation. All studies found that, as BW_{Set} increased, muscle activity generally decreased across most muscles studied, with some key exceptions. Mercer et al. [26] found that the biceps femoris was not significantly altered by unweighting. Likewise, Hunter et al. [24] reported that unweighting did not have a significant impact on medial and lateral hamstring activity during stance, or hip adductor activity during swing. Sainton et al. [20] found that changes in muscle activity across various phases of the stride cycle differed by muscle (i.e., gastrocnemius activity was actually increased during the braking phase during unweighting) and were dependent upon the magnitude of unloading. Additionally, Sainton et al. [20] reported slight alterations occurred during reloading at 100 % BW_{Set} following unweighting. A summary of the neuromuscular activation findings from each study is presented in Table 5.

3.3 Physiologic Variables

Eight studies [16, 20, 22, 23, 27–30] met the inclusion criteria for evaluation of metabolic parameters. All studies that examined $\dot{V}O_2$ and HR during submaximal running found these parameters to decrease with unweighting. Raffalt et al. [16] reported decreased minute ventilation during unweighted submaximal running, despite unchanged respiratory rate. McNeill et al. [29] also reported a decreased respiratory exchange ratio. McNeill et al. [29] and Ruskstuhl et al. [30] both reported decreased rating of perceived exertion (RPE) with unweighted submaximal

Table 4 Influence of lower body positive pressure treadmill unweighting on stride characteristics during running

Study	Stride length	Stride rate	Contact time	Flight duration	Notes
Cutuk et al. [19]	↑ or ↔				Visual data suggested increase in stride length during running, but statistical analysis of combined walking and walking data indicated no changes in stride length
Gojanovic et al. [23]	↑	↔ females, ↑ males			
Grabowski and Kram [15]		↓	↑		Contact time increased while stride rate remained unchanged at 100 % BW_{Set} after previous unweighting
Raffalt et al. [16]	↑	↓	↓	↑	
Sainton et al. [20]		↓	↔	↑	Duty factor decreased with unweighting. Braking phase duration decreased at 60 % BW_{Set}, push-off duration was not influenced by unweighting. Flight time increased while stride rate decreased at 100 % BW_{Set} after unweighting

BW_{Set} body weight setting, *LBPPT* lower body positive pressure treadmill, ↑, ↓, and ↔ indicate increase, decrease, and no change, respectively

running, whereas Sainton et al. [20] reported no changes in RPE. Rather than examining changes in RPE across unweighting levels, Hoffman and Donaghe [22] showed that HR and RPE remained the same for a given $\dot{V}O_2$ across various BW_{Set}.

Two studies reported that $\dot{V}O_{2max}$ can be achieved using an LBPPT provided a sufficient speed is used to compensate for unweighting. Raffalt et al. [16] reported that all measured cardiorespiratory parameters remained unchanged at maximal aerobic intensity across BW_{Set}, whereas Gojanovic et al. [23] reported decreased maximal HR and increased RPE at certain BW_{Set} in men and women, as well as decreased lactate at 85 % BW_{Set} in men.

Two studies [27, 28] provided sufficient $\dot{V}O_2$ data in tabular format, and we obtained tabular data from one published study directly from the author [22]. The generalized estimating equation model was statistically significant for both speed and BW_{Set} ($p < 0.001$ for both). The equation developed was as in Eq. 1:

$$\dot{V}O_2(\text{ml O}_2/\text{kg/min}) = 6.493 \times \text{speed (m/s)} + 0.317 \times BW_{Set}(\text{percent}) - 18.232. \quad (1)$$

When observed values were compared with predicted values, the coefficient of determination was $r^2 = 0.880$, indicating the derived equation was generally a very good fit.

Table 6 presents a summary of physiological findings from each study.

3.4 Running Performance

One study [31] was included in the discussion of improving running performance. Gojanovic et al. [31] found that high-intensity interval training on an LBPPT (90 % BW_{Set}) can lead to improvements in $\dot{V}O_{2max}$, velocity at $\dot{V}O_{2max}$, and time to exhaustion at $\dot{V}O_{2max}$; however, over-ground 2-mile time trial time did not improve compared with similar training on a standard treadmill.

4 Discussion

The available research collectively demonstrates that running on an LBPPT is effective in allowing individuals to achieve a given metabolic stimulus with reduced musculoskeletal loading, though with apparent alterations in neuromuscular activation patterns, kinetics, and stride parameters.

4.1 Kinetic Responses

A primary goal of using an LBPPT is to reduce forces imposed upon the musculoskeletal system by providing upward vertical force to counter gravity. The available research indicates that an LBPPT does indeed achieve the desired effect of musculoskeletal unloading, as evidenced by decreased ground-reaction forces and in-shoe loading, and that sufficient unweighting (<60 to 80 %) reduces the active peak below that of the impact peak. Future research examining kinetic responses to using an LBPPT must consider peak ground-reaction force, must differentiate between impact and active peaks, and should also consider impulse. Additionally, as unweighting is increased, a shift in in-shoe regional loading towards the forefoot occurs that may result in altered running patterns (most prominent <80 % BW_{Set}) [21]. Thus, future studies exploring biomechanical responses to LBPPT running should account for foot strike type.

Table 5 Influence of lower body positive pressure treadmill unweighting on neuromuscular activation during running

Study	Phase of running	Gluteus maximus	Gluteus medius	Medial hamstring	Lateral hamstring	Biceps femoris	Vastus medialis	Vastus lateralis	Rectus femoris	Hip adductors	Gastrocnemius	Soleus	Peroneus longus	Tibialis anterior	Notes
Hunter et al. [24]	Swing									↔					Arrows represent significant linear regression slopes across BW_{Sets}, but slopes vary between muscles
	Stance	↓	↓	↔	↔		↓	↓	↓		↓	↓	↓	↓	
Liebenberg et al. [25]	Whole stride					↓			↓		↓			↓	Change in muscle activity not directly proportional to change in BW_{Set} for all muscles
Mercer et al. [26]	Whole stride					↔			↓		↓			↓	Change in muscle activity not directly proportional to change in BW_{Set} for all muscles
Sainton et al. [20]	Pre-activation										↔	↔		↓ 60 %	Percentages reflect significance only at specified $\%BW_{Set}$. Vastus lateralis and medialis decreases were at expected stretch reflex activation during stance. After reloading, increase in gastrocnemius EMG during braking vs. pre-unweighting 100 % BW_{Set}
	Braking						↓	↓ 60 %			↓ 80 %	↓ 80 %		↔	
	Push-off										↓ 80 %	↓		↔	

BW_{Set} body weight setting, *EMG* electromyography, *LBPPT* lower body positive pressure treadmill, ↓ represents decrease in EMG activity with unweighting (i.e., increase in EMG with increase BW_{Set}), ↔ represents muscles that were examined but not significantly influenced by BW_{Set}

Table 6 Physiologic responses to unweighted running in lower body positive pressure treadmill

Study	Intensity	$\dot{V}O_2$	Heart rate	VE	RPE	Respiratory frequency	Respiratory exchange ratio	Blood lactate	Notes
Gojanovic et al. [23]	Maximal	↔	↓ M 85 %; ↓ F 100 %, 90 %	↔	↑ M breathing 90 %; ↑ F muscular 100 %			↓ M 85 %	
Hoffman and Donaghe [22]	Submaximal	↓	↓						For a fixed $\dot{V}O_2$, HR and RPE were not influenced by unweighting
Kline et al. [27]	Submaximal	↓							
McNeill et al. [28]	Submaximal	↓							
McNeill et al. [29]	Submaximal	↓	↓		↓		↓		General results—two-way interaction between BW_{Set} and speed reported
Raffalt et al. [16]	Submaximal	↓	↓	↓		↔			
	Maximal	↔	↔	↔	↔	↔	↔	↔	
Ruckstuhl et al. [30]	Submaximal	↓	↓		↓				
Sainton et al. [20]	Submaximal		↓		↔				

BW_{Set} body weight setting, *HR* heart rate, *LBPPT* lower body positive pressure treadmill, *RER* respiratory exchange ratio, *RPE* rating of perceived exertion, *VE* ventilatory equivalent, $\dot{V}O_2$ volume of oxygen consumption, ↓, ↑, ↔ indicate decrease, increase, and no change, respectively

While positive pressure is meant to provide vertical body weight support, Grabowski and Kram [15] and Sainton et al. [20] both reported braking impulses exceeded propulsive impulses, and thus horizontal stabilization also influences biomechanical and physiological responses to LBPPT running. Previous research on normal treadmills demonstrated that a small amount of horizontal assistance decreases metabolic demands and increases peak impact force and vertical loading rate without influencing active peak force [32, 33]. While these findings suggest that the LBPPT apparatus provides some horizontal stability in the anterior–posterior direction, it is possible that it also provides mediolateral stability. The added mediolateral stability may contribute to the decreased metabolic cost of running. While this seems likely, no published research has yet explored this possibility.

It is important for LBPPT users and clinicians to be aware that biomechanical alterations to unweighting do not necessarily occur proportionately to BW_{Set}. For instance, Smoliga et al. [21] reported that BW_{Set} on the LBPPT does not represent the actual percentage of maximum ground-reaction force but rather the percentage of maximum ground-reaction force beyond the user's standing body weight. For instance, while running at preferred training speed at the 100 % BW_{Set}, the user lands at approximately 2.3 times his/her body weight, which is 1.3 body weights more than standing at rest. At 20 % BW_{Set}, users landed at 1.2 body weights, which is 0.2 body weights, or 20 % more force, than standing at rest. However, this is approximately 50 % of the actual maximal ground-reaction force compared with 100 % BW_{Set} ($1.20 \div 2.32 = 51.7$ %). In other words, 20 % BW_{Set} does not equate to 20 % of maximal ground-reaction force, and thus biomechanical responses do not scale directly proportionately to BW_{Set}. On this note, it is important to recognize that unweighting does not simply reduce the magnitude of a given biomechanical parameter but rather causes a complex series of kinetic changes. For instance, three studies [15, 20, 21] demonstrated that the active peak is reduced disproportionately greater than the impact peak, and one study [21] demonstrated that the relative load within different regions of the foot is also altered.

4.2 Neuromuscular Responses

The available LBPPT literature indicates that muscles respond differently to different magnitudes of unweighting, and there is variability in muscle activation response to unweighting between muscles, which may depend on the function of the specific muscles during running. The data from Sainton et al. [20] indicate that activation is not significantly decreased in certain muscles until considerable unweighting occurs (e.g., significant differences present at 60 % BW_{Set}, but not 80 % BW_{Set}). Interestingly, other muscles actually experience significant changes with some unweighting (i.e., 80 % BW_{Set}) but not with further unweighting (i.e., 60 % BW_{Set}). While some muscles consistently experience decreased activation with greater unweighting (e.g., tibialis anterior, rectus femoris), Hunter et al. [24] and Mercer et al. [26] both reported that hamstring activity did not continue to decline with reduced BW_{Set}. Hunter et al. [24] also reported that hip adductor muscles remained relatively unchanged with unweighting, which is likely related to unweighting having less of an influence on the need for stabilization within the frontal plane compared with propulsion.

4.3 Kinematic Responses

Kinematic adjustments to LBPPT running are not as well defined and, in the case of stride parameters, are inconsistent. Use of an LBPPT requires the user to wear tight neoprene shorts that are then attached to the treadmill. This may directly and indirectly change the range of motion of certain joints. For instance, the waist seal of the LBPPT may limit upward displacement during ambulation, which could secondarily decrease knee range of motion [19]. Further, conflicting findings in kinetic and kinematic responses between studies strongly indicate that the nature of biomechanical responses may depend on the magnitude of unloading (e.g., 40 % BW_{Set} may produce different results than 80 % BW_{Set}), running speed, fitness levels, treadmill running experience, and perhaps previous LBPPT experience. This is likely the case for stride parameters, where conflicting findings may be a result of vastly different speeds between protocols. Indeed, there is evidence of an accommodation effect, such that multiple trials of unweighted running may be necessary to achieve stable metabolic measurements [34].

4.4 Cardiometabolic Responses

These biomechanical changes seen with the LBPPT all contribute to less metabolic cost. Specifically, if the body's mechanical power output requirement is lowered, neuromuscular activation is reduced, and therefore there is a decreased need for adenosine triphosphate (ATP) production. Thus, it is not surprising that, as BW_{Set} is reduced within a given speed, $\dot{V}O_2$ demand is decreased, and thus, HR and ventilation are also reduced. Kline et al. [27] reported that the proportion of metabolic demand to BW_{Set} was found to be near equivalent for 70–90 % BW_{Set}; however, at the extreme ends, the proportion of metabolic demand differed significantly from the proportion of BW_{Set}. Thus, individuals training on an LBPPT with the goal of achieving a specific metabolic stimulus while unweighted may need to increase the treadmill speed or incline to achieve the desired overall metabolic stimulus, and it is even possible to achieve $\dot{V}O_{2max}$ at reduced BW_{Set}. According to Hoffman and Donaghe [22], the relationship between HR and $\dot{V}O_2$ remained unchanged with alterations in BW_{Set}, which suggests that HR monitoring may be effective for monitoring running intensity on an LBPPT. This is also consistent with the recommendation by McNeill et al. [29] to base exercise prescription on HR due to individual variability. However, given that unweighting elicits different responses between muscles (i.e., neuromuscular activation in the rectus femoris to a greater magnitude than the hamstring group), unweighting may produce a different profile of local muscular metabolic demands, which ultimately result in a similar whole-body $\dot{V}O_2$. This further echoes the notion that individuals participating in unweighted training on an LBPPT should be cognizant of the alterations in muscular stimulus compared with normal unweighted running.

It is important to note that the cardiometabolic demands of running at 100 % BW_{Set} on an LBPPT are lower than running on a regular treadmill. McNeill et al. [34] attributed the decreased metabolic demand at 100 % BW_{Set} to the inflation of the chamber, which likely did have physiological effects by decreasing vertical ground-reaction force ~7 %. However, it is also possible the added two-dimensional horizontal support of the LBPPT apparatus may also contribute to decreased metabolic demand at 100 % BW_{Set}. Although the magnitude of the additional vertical and horizontal support at 100 % BW_{Set} may seem minor, it can have major physiological implications. For instance, Raffalt et al. [16] found that time to exhaustion during a $\dot{V}O_{2max}$ test was 34.5 % longer when performed on an LBPPT at 100 % BW_{Set} than on a standard treadmill, which suggests the supporting apparatus itself influenced running performance.

4.5 Training Implications

Given that LBPPTs are intended for rehabilitating injured individuals, preventing injuries, and enhancing performance, it is imperative that training benefits achieved on LBPPTs translate to over-ground running. Two studies reported some acute adjustments that occurred during reloading (i.e., running at 100 % BW_{Set} following unweighting). Sainton et al. [20] found reloading altered stride characteristics following 60 % BW_{Set}, altered stride kinetics following 80 % BW_{Set}, and increased neuromuscular activity and physiologic intensity following both unweighting conditions. Conversely, Grabowski and Kram [15] found kinetics remained unchanged but contact time increased following an unweighting protocol. Conflicting findings may reflect different research protocols but nonetheless suggest that prior unweighting does acutely influence normal running mechanics, though the duration of such alterations remains unknown. Likewise, these studies only utilized a few minutes of LBPPT training, and the results may not be representative of the alterations that would occur following a typical training session. Thus, research is insufficient to determine whether neuromuscular and biomechanical alterations that occur on LBPPTs influence over-ground running and the consequences of long-term LBPPT training on over-ground running mechanics.

Gojanovic et al. [31] found 4 weeks of high-intensity interval training on an LBPPT (90 % BW_{Set}) improved multiple physiologic performance parameters, including $\dot{V}O_{2max}$ and velocity at $\dot{V}O_{2max}$, but resulted in similar over-ground 2-mile time trial performance compared with training on a normal treadmill. This suggests that even if LBPPTs do modify running mechanics as described above, they do not do so in a way that negatively or positively influences running performance. It remains unknown whether LBPPT training can simply replicate the benefits of over-ground running, albeit with a lower musculoskeletal impact, or whether strategically designed unweighted running protocols can actually enhance performance beyond that attainable through over-ground running alone. Although one study alone is not sufficient to draw conclusions regarding longer-term performance adaptations to unweighting, the results do suggest that LBPPT training does translate to over-ground running performance (i.e., training on an LBPPT can be beneficial for improving track or road race performance). Thus, it may be possible for injured or injury-prone athletes to realize improvements through training on an LBPPT; however, the faster speeds (or inclines) necessary to achieve sufficient physiologic stimulus during unweighting may ultimately negate some of the desired musculoskeletal unloading. In addition, there may be potential for increased injury risk via the faster speeds altering running mechanics or requiring different neuromuscular activation patterns than would normally be used. Thus, further research should examine long-term effects of LBPPT training on both injury risk and performance in both healthy and injured athletes. The effect of incline on LBPPT running should also be explored.

Through evaluating the available data, we determined that three studies [22, 27, 28] could be used to develop an equation to predict $\dot{V}O_2$ based on running speed and BW_{Set}

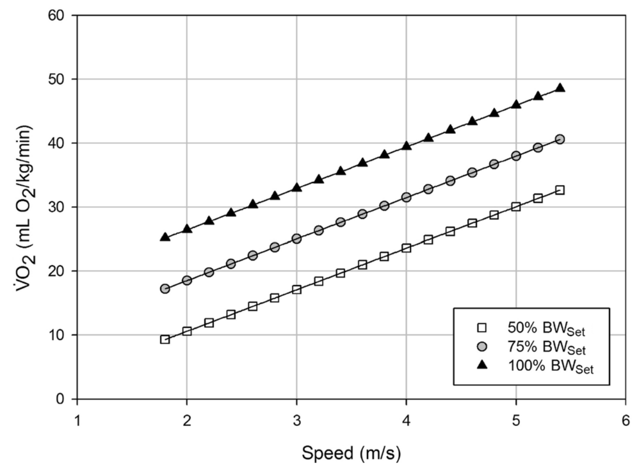

Fig. 2 Predicted relationship between running speed and $\dot{V}O_2$ at BW_{Set} 50, 75, and 100 % based on pooled data from three studies. This figure may be used to visualize what running speed would need to be prescribed at a given LBPPT BW_{Set} to elicit an equivalent $\dot{V}O_2$ at another BW_{Set}. For example, to achieve a $\dot{V}O_2$ of approximately 30 ml/kg/min, a speed of 2.5 m/s could be used at 100 % body weight (30.1 ml/kg/min), 3.8 m/s could be used at 75 % body weight (30.5 ml/kg/min), and 5 m/s could be used at 50 % body weight (30.1 ml/kg/min). BW_{Set} body weight setting, *LBPPT* lower body positive pressure treadmill, $\dot{V}O_2$ volume of oxygen consumption

(Eq. 1). Figure 2 shows a graph of the equation at BW_{Set} 100, 75, and 50 % with corresponding speeds and $\dot{V}O_2$. As shown by Fig. 2, to achieve a $\dot{V}O_2$ of approximately 30 ml O_2/kg/min, a speed of 2.5 m/s would be required at 100 % BW_{Set}, 3.8 m/s would be needed at 75 % BW_{Set}, and 5 m/s would be needed at 50 % BW_{Set}. This equation also shows that within a given running speed, each 10 % decrease in BW_{Set} is associated with an approximately 3.4 ml O_2/kg/min reduction in $\dot{V}O_2$. However, this model only represents three datasets, with treadmill speeds ranging from 1.79 to 5.36 m/s and LBPPT settings of 50–100 % BW_{Set} and should not be extrapolated beyond these limits. Nonetheless, the strong coefficient of determination indicates that the $\dot{V}O_2$ response to various BW_{Set} and running speeds was generally consistent between these three studies, which suggests that physiological response may also be consistent across individuals.

4.6 Clinical Implications

The wealth of research on biomechanical and physiological responses to LBPPT provides some insight for clinical usage. As noted in Sect. 4.1, the BW_{Set} does not accurately reflect the absolute magnitude of peak ground-reaction force production, and clinicians must be aware that running at 50 % BW_{Set} is not actually equivalent to half of the musculoskeletal impact of normal running. Likewise, LBPPTs alter regional in-shoe loading, such that reductions in ground-reaction force do not necessarily result in uniformly distributed musculoskeletal loads [21]. As such, caution may be warranted in excessive use of LBPPTs for individuals with foot pathology (e.g., metatarsal stress fractures, plantar fasciitis), until more research in this area is available. The available neuromuscular data [20, 24–26] have important implications for clinicians utilizing LBPPTs for rehabilitating injured athletes. The findings by Sainton et al. [20] emphasize the notion that LBPPT unweighting has a complex effect on neuromuscular activation, and reducing BW_{Set} does not simply reduce muscle activity in a linear manner. Based on neuromuscular activation patterns in healthy athletes, individuals with calf or Achilles tendon injuries may benefit from unweighting, whereas individuals with groin or hamstring injuries may not receive any benefit from LBPPT running. While this concept seems sound, future clinical trials will be needed to confirm this. It is especially important for clinicians to appreciate this concept, as the reduced perception of overall exertion [29, 30] and impact [15, 16, 19–22] provided by unweighting on LBPPTs may provide athletes with a false sense that these specific muscle groups are also under less stress. The available research does indicate that LBPPTs produce favorable responses for training [31], and case studies [13, 14] and pilot studies [12] support its benefit in rehabilitation, but long-term studies in both realms are necessary for developing strong evidence-based recommendations for clinical use.

4.7 Terminology

The terminology used across the LBPPT literature varies significantly, and it is often difficult to distinguish whether the methods refer to the amount of body weight support provided (e.g., 20 % upward vertical force), the reduction in body weight relative to normal gravity (e.g., 80 % of standard conditions), the targeted body weight setting on the LBPPT, or the actual measured body weight on the treadmill. For example, some authors refer to no body weight support from the LBPPT as 0 %, while others refer to this as 100 % because the LBPPT setting would be set to 100. Thus, the terminology used can be very unclear and even misinterpreted. While both "unweighting" and "body weight support" may be applicable to LBPPTs, we believe the term "unweighting" is preferable in the context of LBPPTs. Harness systems and LBPPTs can be considered a more general type of "body weight support" but are unlike other ambulation aids, such as walkers and canes, which also redistribute forces to other areas of the body. However, the body weight support offered by harness systems and LBPPTs is external, such that users do not need to contract musculature elsewhere to support their lower body (i.e., activating the torso and arm musculature to support the body when walking with a cane). As such, we use the terminology in Table 1, and propose that this nomenclature be used throughout the LBPPT literature to minimize confusion.

4.8 Limitations

Synthesis of research regarding LBPPTs reveals considerable insight into the integration of biomechanical and physiological responses to unweighting; however, there are some limitations to the current body of research. All but two of the studies that met inclusion criteria for this systematic review included a limited number of sessions using an LBPPT, and therefore did not explore chronic adaptations to LBPPT running. Most of the studies used men only, yet Gojanovic et al. [23] demonstrated that men and women do respond differently to using an LBPPT in some parameters. Thus, further research examining responses to LBPPT training in females may be necessary, as sex differences in anthropometric factors may be influential. Additionally, the diversity of LBPPT protocols used, combined with the different types of comparisons performed within a study, makes it difficult to compare results between studies. For instance, Sainton et al. [20] and Grabowski and Kram [15] were in agreement about active peak being the most responsive kinetic parameter in response unweighting. Changes in loading rate seemed to be more responsive to unweighting in the study by Sainton et al. [20] than in the work by Grabowski and Kram [15]. However, Sainton et al. [20] measured changes between 60 and 80 % BW_{Set}, and between 80 and 100 % BW_{Set}, whereas, Grabowski and Kram [15] compared changes between 50 and 75 %. Additionally, the kinetic studies only examined ground-reaction forces and do not provide any insight into how unweighting influences joint moments or joint compression forces. Finally, the majority of the studies included in this systematic review used products made by Alter-G; however, slight updates have been made in the design of their LBPPT devices. Although the methodology from early and recent studies suggests that the same general principles all apply, it is possible that some changes in biomechanical or physiological responses could arise from differences in design.

5 Conclusions

The commercial availability of LBPPTs has increased accessibility to unweighted running; thus, research on this topic has rapidly expanded. This is the first systematic review on this topic, and the results reveal that the collective body of literature is sufficient to describe general biomechanical and physiological responses to unweighted running. Running on an LBPPT is associated with a variety of kinetic adjustments, most notably disproportionate reductions in the active vertical ground-reaction force peak relative to the impact peak and propulsive impulses relative to braking impulse, as well as a shift in in-shoe regional loading towards the forefoot. The synthesis of the literature provides evidence that lower BW_{Sets} are associated with decreased musculoskeletal and metabolic demands, and that faster treadmill speeds can be used to raise the physiologic stimulus without fully countering the reduced musculoskeletal loading provided by the LBPPT. Although external mechanical support from the LBPPT apparatus ultimately reduces metabolic stimulus, the loads on the hamstring and hip adductor muscle groups are not reduced to the same magnitude as that of other leg muscles. As such, clinicians must be aware that LBPPT does not simply 'reduce impact' but also changes biomechanics and musculoskeletal loading in a rather complex manner, and that caution may be warranted when using the LBPPT for treating certain types of musculoskeletal injuries. The magnitude of biomechanical and physiological alterations appears to become more exaggerated at BW_{Set} <70 %, thus, individuals looking to train while receiving the benefits of unweighting while minimizing changes in running mechanics are encouraged to stay above this threshold. There is some evidence that unweighted training on an LBPPT can effectively translate into improved performance during over-ground running, though more research in this area is needed. Further research is needed regarding the efficacy of LBPPT for individuals with specific musculoskeletal injuries so that optimized rehabilitation protocols can be developed.

Compliance with Ethical Standards

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