Examining Change in Gait and Impact Forces on a Lower Body Positive Pressure Treadmill at 60% VO_{2peak}

Original Research

Julia Phillips[1], Trace Dominy[1], Katherine Tibbs[1], Brooke Gilmore[1], Thomas Andre[1]

[1]*Univeristy of Mississippi, Oxford, MS, USA*

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Abstract

Introduction: Running is one of the most popular forms of physical activity in the world providing many health benefits but also leads to an increase in overuse and tendinopathy injuries. Lower body positive pressure treadmills (LBPPT) reduce body-weight (BW) impact, benefiting individuals with musculoskeletal conditions or undergoing rehabilitation. Previous research indicates LBPPT could be a potential training alternative or reintroducing exercise sooner in rehabilitation process. The purpose of this study was to examine average impact force and accumulated impact force over the course of a 5-km run at 60% of VO_{2peak} at various % BW to examine if there is a potential alternative to over-ground running.

Methods: In total, 20 aerobically fit individuals completed a VO_{2peak} and 5 counterbalance trials at 100% BW on a regular treadmill and 100%, 90%, 80% and 70% BW on a LBPPT. A linear mixed-effect model was used for all insole data and repeated-measures analysis of variance (ANOVA) tests of within-subject's effects was performed for each variable.

Results: The results showed a significant difference in the time it took to run the 5-km as the BW decreased (100% RT: 33.8 ± 1.1 min; 100% LBPPT: 31.8 ± 0.9 min; 90%: 30.3 ± 1.0 min; 80%: 28.0 ± 1.0 min; 70%: 24.6 ± 0.7 min; $p < 0.05$). Average impact force per step did not differ between conditions ($p > 0.05$), but the accumulated impact over the course the 5-km did significantly decrease as BW decreased (100% RT: 8283.5 ± 342.7 kN; 100% LBPPT: 8203.8 ± 326.2 kN; 90%: 6953.9 ± 348.6 kN vs. 80%: 6953.9 ± 270.0 kN; $p < 0.001$).

Conclusions: In conclusion, the LBPPT treadmill provides a possible alternative to runners to maintain the same aerobic intensity while accumulating less force and stress on the lower extremity over a fixed distance.

Key Words: Running, Alternative Training, Injury, Impact Force

Corresponding author: Julia Phillips, jpphill4@olemiss.edu

Introduction

Running is one of the most accessible and popular forms of exercise worldwide, owing to its well-documented health benefits. However, it also has high rates of injuries and as many as 65% of runners reporting an overuse injury, majority affecting the lower body [1–3]. Weekly mileage has commonly been cited as a risk factor for injury, where Macera found it to be the most significant predictor in habitual runners over a 12-month span [4]. Others have found no difference between injured and uninjured runners weekly mileage suggesting it could be a combination of stressors in addition to mileage [1]. Of those who sustain injuries, 80% are overuse in nature, predominantly involving the lower back and legs [5–7]. Weekly mileage is commonly utilized by runners to quantify workload, but training load is influenced by training intensity that influences external loads like pace and duration and internal loads [8]. There are a multitude of factors that can play a role in overuse injuries including applied forces, behavioral and physiological risk factors [1]. One potential strategy to reduce certain internal and external loads while maintaining mileage is the lower body positive pressure treadmill (LBPPT) by minimizing the weight experienced by the runner. In theory, it could be utilized to reduce stress on the lower extremity while still providing enough stimulus to maintain aerobic capacity. To date, most research with the LBPPT has focused on physiological and kinematic changes across varied bodyweights (BW) at constant velocities. Although the impact of maintaining a relative aerobic intensity (oxygen consumption: VO_2) across various BW has not been examined.

The use of a LBPPT has emerged as an innovative approach to examining and mitigating the effects of running-related fatigue and impact and ground reaction forces (GRF). When running at set velocities, GRF was reduced with reduction in BW [9]. When velocity is increased, there is an increase in impact peak and plantar force but the increase can be minimized with a LBPPT [10]. One of the primary benefits of using an LBPPT is its ability to reduce vertical and horizontal forces experienced by runners, thereby potentially minimizing the risk of overuse injuries and allowing for more extensive training sessions at a consistent intensity [11]. Previous research has focused on examining instantaneous measurements such as ground reaction force per step or joint kinetics, but few have investigated accumulated load over a fixed distance. From an overuse and injury standpoint, accumulated load and repetitive submaximal loads are related to the accumulated micro damage [12]. As BW is decreased, runners can maintain training volume without the cumulative impact that often leads to injuries such as stress fractures or tendinopathies [13]. The reduction in GRF on an LBPPT has also been associated with changes in gait mechanics, including alterations in stride length, cadence, and foot strike patterns, which can influence overall running economy [14].

Therefore, the purpose of this study was to examine changes in gait characteristic, average impact force per step and accumulated impact force during a 5-km run at a fixed 60% VO_{2peak} intensity across various BW conditions. It was hypothesized that by reducing BW, velocity would have to increase leading to a reduce or similar impact per step, but the duration of the run would be decreased leading to a decrease in the accumulated impact force.

Methods

Participants

Twenty aerobically active runners (age 18-30) volunteered to participate in the study. All participants completed an informed consent, and the study procedures were approved by the university's institutional review board. Participants had been running at least three times per week for the previous six months and reported no lower extremity injuries in the three months prior to the study.

Table 1. Participant characteristics.

Variable	Age (years)	Mass (kg)	Height (cm)	Total % BF
All (n = 20)	20.7 ± 1.3	63.5 ± 8.6	169.7 ± 6.9	22.0 ± 6.0
Male (n = 7)	20.9 ± 0.7	71.2 ± 9.7	174.9 ± 8.4	16.0 ± 3.7
Female (n = 13)	20.5 ± 1.6	59.4 ± 4.2	166.8 ± 4.0	25.2 ± 4.2

Mean ± standard deviation for all participants (n = 20), males (n = 7) and females (n = 13). BF = body fat.

Protocol

At the first visit, participants completed the informed consent, Physical Activity Readiness Questionnaire (PAR-Q) and medical history questionnaire. After completion of the paperwork, participants rested quietly for 5 minutes, after which resting blood pressure and heart rate were measured. Body composition was collected using a dual x-ray absorptiometry (DEXA) (Horizon DXA System, Hologic, Inc., Marlborough, MA, USA) shown in Table 1.

Following the DEXA scan participants were fitted with a Polar H10 heart rate monitor (Polar, Stamford, CT, USA), compression shorts for the LBPPT (Boost Treadmills, Russian, OH, USA) and Digitsole Pro shoe inserts (Digitsole, Sunnyvale, CA, USA). The insoles have demonstrated good reliability and validity for measuring cadence, stride length, ground contact time, and impact force (maximum vertical ground reaction force per step) compared with gold-standard laboratory equipment (ICC = 0.88–0.994) [15,16]. Participants were then familiarized with the OMNI Pictorial Rate of Perceived Exertion (RPE) Scale (0-10), as well as the perceived muscle soreness and readiness scales to ensure participants were in similar perceived states before each trial. Subsequently, participants then were equipped with a Hans Rudolph mask connected to a two-way non-rebreathing valve for metabolic gas analysis using a Parvo Medics

TrueOne 2400 system (Parvo Medics, Sandy, UT, USA). Oxygen uptake (VO_2), minute ventilation (VE), and respiratory exchange ratio (RER) were recorded in 30-second averages. RPE and heart rate were recorded every minute during exercise testing.

Participants then underwent a graded exercise test on a LBPPT treadmill ((Boost 2 Microgravity Treadmills, Boost Treadmills, Russian, OH, USA) starting with a 2-minute warm-up at 1.34 m/s (3 mph) and 0% grade, followed by 1-minute stages with velocity increasing 0.45 m/s (1 mph) until 4.02 m/s (9 mph) [17]. Thereafter, the treadmill grade increased by 2% per minute until exhaustion. A valid VO_{2peak} was confirmed when at least two of the following criteria were met: RER > 1.10, heart rate ≥ 95% of age-predicted maximum, and/or an RPE ≥ 9 [18].

Participants then rested for 5-minutes before heart rate and blood pressure were measured to ensure they returned toward baseline levels. Participants were instructed to wear the same shoes for all visits and to refrain from exercise 24 hours before each lab visit. Visits 2-6 were completed in a randomized and counterbalanced order, participants completed a 5-km run at 100% BW on a regular treadmill (TrackMaster TMX428, Full Vision, Inc., Newton, KS, USA) and at 100%, 90%, 80%, and 70% BW on the LBPPT. Subsequent visits (2–6) were scheduled at approximately the same time of day and separated by at least 48 hours.

Upon arrival to the lab, body mass was recorded. Following a 5-minute seated rest, baseline blood pressure, heart rate, perceived readiness, and muscle soreness were assessed. Participants were then equipped with a heart rate monitor for monitoring, appropriate compression shorts (for LBPPT trials), Digitsole shoe insoles, and a Hans Rudolph mask. Each session began with a 5-minute warm-up at the designated % BW to allow acclimation to the treadmill condition. Following the warm-up, the treadmill was slowed down to 0 m/s. The velocity was then adjusted by a researcher until the participant reached 60% of their previously determined VO_{2peak} (achieved within approximately 5 minutes). Once steady state was reached, the 5-km run began. During the run, time and velocity were recorded every kilometer. Following the completion of the run, participants were seated for 5-minutes prior to measuring heart rate and blood pressure to ensure participants return back to baseline values.

Statistical Analysis

Statistical analysis was performed using SPSS 29.0 software (Chicago, IL) to examine how cadence, stride length, average impact force/step, accumulated impact force and change across different BW conditions (100% RT, 100%, 90%, 80%, 70% on LBPPT) for running 5-km at 60% VO_{2peak} test. Descriptive statistics including mean, standard error, and 95% confidence interval estimates were computed for each dependent variable across the five different conditions and body weight percentages. A linear mixed-effect model was used for all the insole data and repeated-measures analysis of variance (ANOVA) tests of within-subject's effects was performed for each variable. Tests of sphericity assumptions were used for potential violations of sphericity in repeated measures data, if a violation was found the Greenhouse-Geisser correction factor was applied. Significant differences were determined using Bonferroni post-hoc test. Effect sizes for the linear mixed-effects models were calculated and reported as partial eta squared (ηp^2). Effect sizes were interpreted as small (0.01), medium (0.06), and large (0.14). The alpha-levels were set at $p < 0.05$ to determine statistical difference. An a priori power analysis conducted with G*Power (version 3.1) determined that 20 participants were needed in the present study to achieve a power of 0.80 and an effect size of 0.5 ($\alpha = 0.05$) based on previous research related to gait parameters.

Results

In total, 20 runners completed all 6-visits. Of the 20 runners, there were 7 males and 13 females with their aerobic characteristics shown in Table 2.

Table 2. Mean peak oxygen consumption and average 60% VO_{2peak} values.

Variable	VO_{2peak} ($ml \cdot min^{-1} \cdot kg^{-1}$)	60% VO_{2peak} ($ml \cdot min^{-1} \cdot kg^{-1}$)	60% LE VO_{2peak} ($ml \cdot min^{-1} \cdot kg^{-1}$)	60% UE VO_{2peak} ($ml \cdot min^{-1} \cdot kg^{-1}$)
All (n = 20)	48.1 ± 6.9	28.9 ± 4.1	27.4 ± 3.9	30.3 ± 4.3
Male (n = 7)	51.3 ± 6.5	30.8 ± 3.9	29.2 ± 3.7	32.3 ± 4.1
Female (n = 13)	46.4 ± 6.7	27.9 ± 4.0	26.5 ± 3.8	29.3 ± 4.2

Mean ± standard deviation for all participants (n = 20), males (n = 7) and females (n = 13). ml = milliliters; kg=kilograms; min = minutes; VO_{2peak} = peak oxygen consumption; LE = average lower extremity; UE = average upper extremity.

The linear mixed-effects model results are shown in Table 2 highlighting the data between the 5 different 5-km run conditions. Figures 1, 2 and 3 highlight the significant difference between groups for each variable.

Table 3. Running variables across the 5 bodyweight conditions.

Condition	100% RT	100% LBPPT	90% LBPPT	80% LBPPT	70% LBPPT	n_p^2	p-value
Time (min)	33.8 ± 1.0	31.8 ± 0.9	30.3 ± 1.0	28.0 ± 1.0	24.6 ± 0.8	0.947	< 0.001
Cadence (spm)	162.1 ± 1.5	165.3 ± 1.7	164.0 ± 1.8	161.5 ± 1.9	160.6 ± 2.3	0.821	0.205
IFL (kN)	1.54 ± 0.08	1.59 ± 0.07	1.53 ± 0.07	1.54 ± 0.07	1.47 ± 0.06	0.491	0.209
IFR (kN)	1.53 ± 0.07	1.59 ± 0.07	1.56 ± 0.08	1.57 ± 0.08	1.55 ± 0.08	0.397	0.569
Stride Left (m)	1.86 ± 0.05	1.85 ± 0.05	1.98 ± 0.07	2.14 ± 0.08	2.45 ± 0.08	0.902	< 0.001
Stride Right (m)	1.98 ± 0.05	1.96 ± 0.05	2.09 ± 0.07	2.27 ± 0.09	2.53 ± 0.10	0.807	< 0.001
AIF (kN)	8283.5 ± 342.7	8203.8 ± 326.2	7545.4 ± 348.6	6953.9 ± 270.0	5843.0 ± 209.8	0.890	< 0.001

Values are mean ± SE. min = minutes; spm = steps per minute; IFL = impact force left; IFR = impact force right kN = kilonewton; m = meter; AIF = accumulated impact force; RT= regular treadmill; LBPPT = lower body positive pressure treadmill.

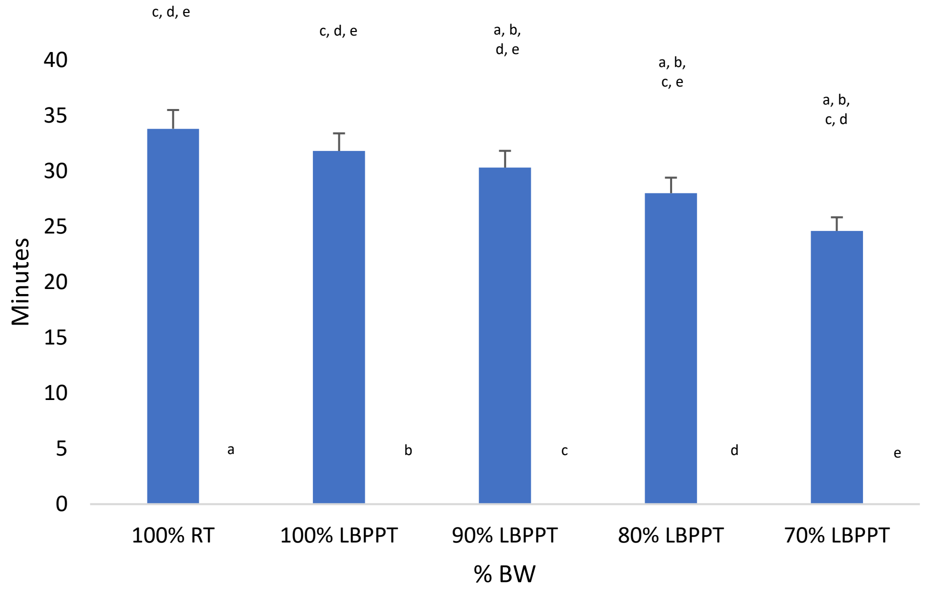

Figure 1. The mean duration to run 5-km across the 5 different conditions at 60% of the participants VO_{2peak}. Completion time decreased progressively as percent body-weight decreases on the LBPPT. Different letters indicate significant differences between conditions ($p < 0.05$). RT= regular treadmill; LBPPT = lower body positive pressure treadmill. a = significantly different from 100% RT; b = significantly different from 100% LBPPT; c = significantly different from 90% LBPPT; d = significantly different from 80% LBPPT; e = significantly different from 70% LBPPT.

There was no significant difference between 100% RT and 100% LBPPT ($p = 0.118$) but there was a significant difference across all other conditions with a large effect size) for the average duration it took participants to complete the 5-km run ($p < 0.05$; $\eta p^2 = 0.947$) (Figure 1). The participants' cadence also had significant differences amongst different conditions with a large effect size ($\eta p^2 = 0.821$). The 100% RT and 100% LBPPT treadmill conditions showed a significant difference in cadence (spm), with the 100% LBPPT condition producing a higher cadence (165.3 ± 1.7 spm) compared to the 100% RT condition (162.1 ± 1.5 spm; $p < 0.001$). Additionally, cadence in the 100% LBPPT condition was significantly higher than in the 80% LBPPT condition (161.5 ± 1.9 spm; $p = 0.027$). The 90% LBPPT condition (164.0 ± 1.8 spm) also resulted in a significantly higher cadence than the 100% RT condition (162.1 ± 1.5 spm; $p = 0.031$).

Stride length on the left leg did not differ significantly between the 100% RT and 100% LBPPT conditions (100% RT: 1.86 ± 0.05 m vs. 100% LBPPT: 1.85 ± 0.05 m; $p = 1.000$). However, all other conditions showed significant differences, with stride length increasing as % BW decreased resulting in a large overall effect size for the left leg ($\eta p^2 = 0.902$). Similar results were observed for the right leg, where no significant difference was found between the 100% RT and 100% LBPPT conditions (100% RT: 1.98 ± 0.05 m vs. 100% LBPPT: 1.96 ± 0.05 m; $p = 1.000$). Additionally, there was no significant difference in right-leg stride length between the 80% and 70% LBPPT conditions (80%: 2.27 ± 0.09 m vs. 70%: 2.53 ± 0.10 m; $p = 0.050$). Similar trends were seen that as % BW decreased the stride length increased with a similarly large effect size for the right leg ($\eta p^2 = 0.807$).

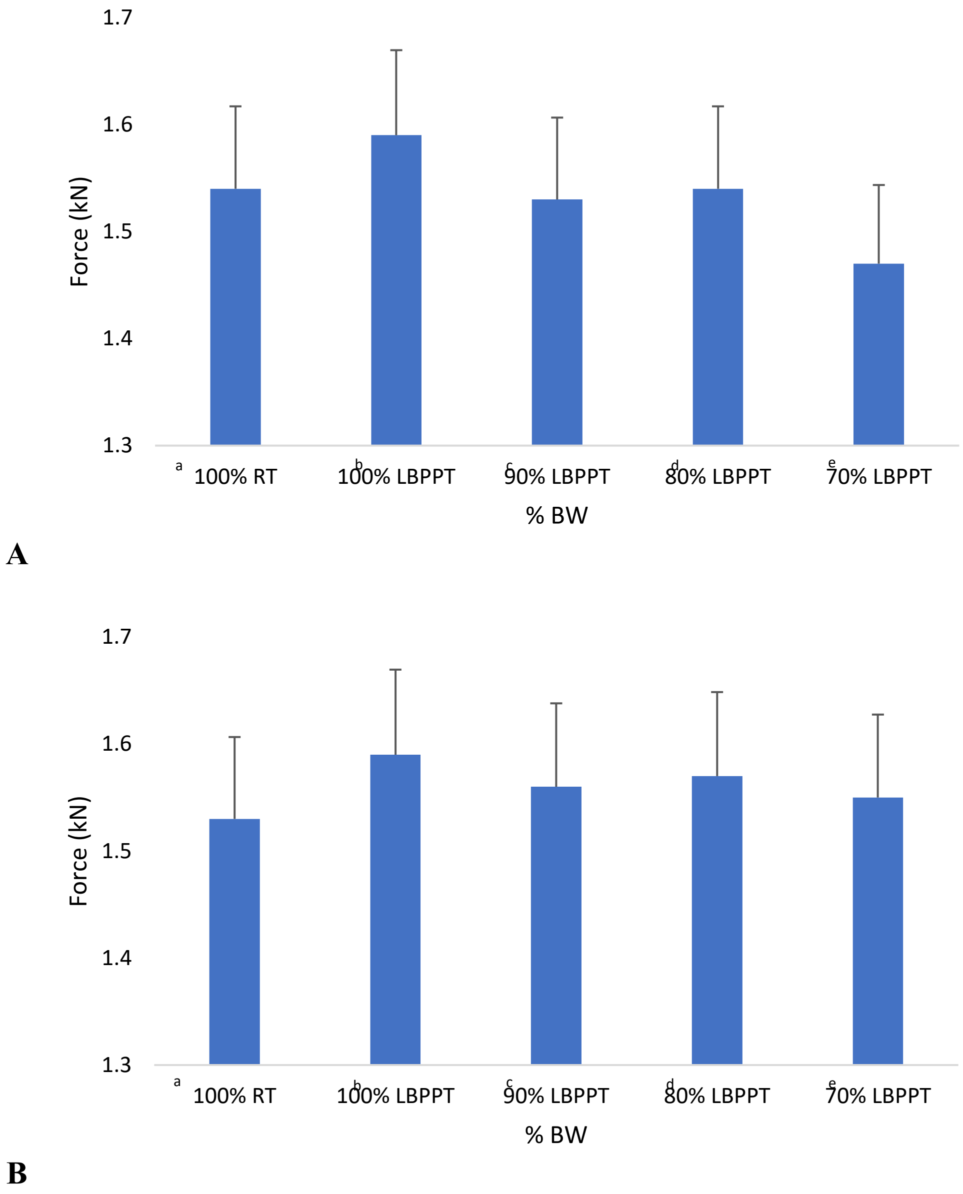

Figure 2. The average impact force for the left (A) and right leg (B) across the 5 conditions at 60% of the participants VO_{2peak}. Average impact force per step remained relatively consistent across conditions with no significant differences between conditions. Different letters indicate significant differences between conditions ($p < 0.05$). RT= regular treadmill; LBPPT = lower body positive pressure treadmill.

The average impact force across both the left and right legs did not differ significantly across the five conditions despite a large effect size observed for the ($\eta p^2 = 0.491$) and right leg ($\eta p^2 = 0.397$). When examining accumulated impact force across the five runs, no significant difference was found between the 100% RT and 100% LBPPT conditions (100% RT: 8283.5 ± 342.7 kN vs. 100% LBPPT: 8203.8 ± 326.2 kN; $p = 1.000$). Additionally, there was no significant difference between the 90% and 80% LBPPT conditions (90%: 6953.9 ± 348.6 kN vs. 80%: 6953.9 ± 270.0 kN). Accumulated impact force demonstrated a large overall effect size across conditions ($\eta p^2 = 0.890$), indicating meaningful reductions in cumulative mechanical exposure as % BW decreased.

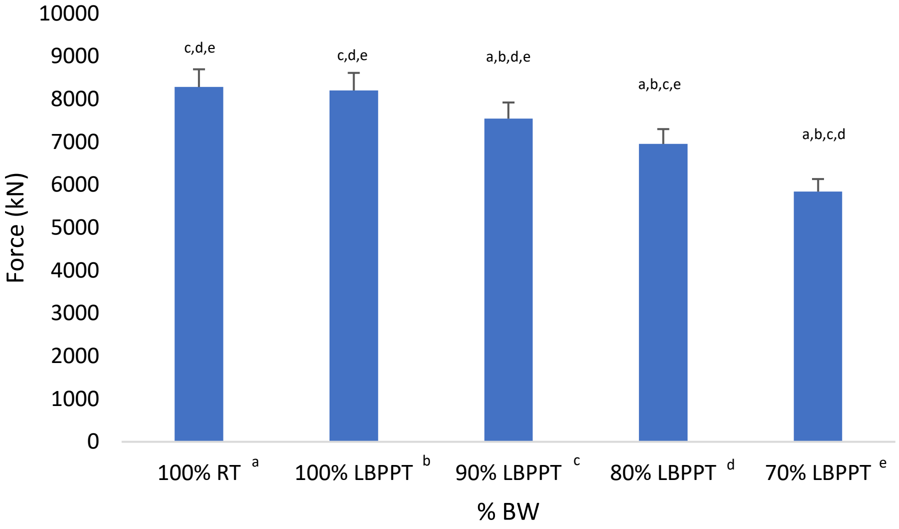

Figure 3. The average accumulated impact force for the left and right leg across the 5 conditions at 60% of the participants VO_{2peak}. Accumulated impact force progressively decreased as percent body-weight decreased with no significant difference between the 100% LBPPT and RT conditions. Different letters indicate significant differences between conditions ($p < 0.05$). RT= regular treadmill; LBPPT = lower body positive pressure treadmill.

Discussion

The purpose of this study was to examine changes in gait characteristics and impact forces during a 5-km run performed at various BW percentages while maintaining a fixed relative aerobic intensity (60% VO_{2peak}). The results showed there was no significant difference in the average impact force, which is the average of the maximal ground reaction force per step, across conditions despite reductions in % BW. The increase in velocity as % BW decreased appeared to offset one another. However, accumulated impact force, which reflects the total impact force experienced over the 5-km run, differed significantly between the different BW conditions (Figure 3). There was no significant difference between the 100% BW conditions on the regular treadmill or the LBPPT due to similar velocities but as BW decreased the accumulated force across the 5-km run decreased. These findings suggest that reducing BW with the LBPPT may allow runners to maintain a comparable aerobic stimulus while reducing cumulative mechanical loading exposure during a fixed-distance run.

Average impact force per step remained consistent across all conditions, whereas the time required to complete the 5-km run decreased significantly as % BW decreased while running velocity increased to maintain the target intensity of 60% VO_{2peak}. On average the 70% LBPPT conditions resulted in substantially faster 5-km times than the 100% regular treadmill condition (70% LBPPT: 24.6 ± 0.7 min vs. 100% RT: 33.8 ± 1.1 min). The increase in running velocity observed with decreasing BW was also accompanied by changes in cadence. As % BW decreased on the LBPPT, cadence decreased with the higher running velocity. The reduction in accumulated impact force was primarily due to faster 5-km running velocities at lower % BW, despite the clamped aerobic intensity. These findings suggest that reducing % BW on the LBPPT may reduce accumulated impact force and overall mechanical exposure while maintaining a similar aerobic intensity.

The observed changes in gait reflect the reductions in % BW and increased velocity required to maintain a fixed aerobic intensity. Stride length increased for both legs as % BW decreased and velocity increased. Cadence also decreased across LBPPT conditions. Previous research has shown that running velocity independently influences gait mechanics, including stride length and cadence. Therefore, the biomechanical adaptations observed in the present study cannot be attributed solely to BW support provided by the LBPPT. Rather, the interaction between unloading and increased velocity likely contributed to the gait alterations observed across conditions.

By reducing % BW on the LBPPT, accumulated impact force and overall mechanical exposure can be minimized while runners maintain a similar aerobic intensity, potentially having practical applicatiosn during congested training periods or in a rehabilitation setting as an individual is returning from an injury. It may also be advantageous for runners performing "doubles" (two runs per day) or recovery runs, as it minimizes accumulated impact force while maintaining aerobic fitness. Additionally, stride length increased for both legs as % BW decreased and velocity increased. While this may enhance performance, it could pose challenges in rehabilitation, particularly for runners with hamstring injuries, as longer strides may lead to overstriding and exacerbate injury risk. Although not examined on the LBPPT, previous data suggest overstriding leads to elongation of the hamstring musculature and greater GRF [20]. While impact force per step was maintained when running at a similar relative aerobic intensity, the reduction in overall mechanical exposure may still have important implications for populations commonly utilizing LBPPTs, such as injured runners, older adults, and clinical rehabilitation populations. However, further research is needed to determine whether similar physiological and biomechanical responses occur in these populations.

This study was not without limitations. A potential limitation of the study was the loss of some data due to technical errors with insole sensors. These insoles have been validated showing excellent reliability for cadence, stride length and loading time when compared against the gold standard in Vicon (ICC = 0.990-0.912) [15] and another study finding similar results with average ICC for the same variable (ICC = 0.997 – 0.907) [16]. Future research should investigate whether muscle activation patterns vary across different % BW at a fixed aerobic intensity, to determine if LBPPT running replicates the muscular loading patterns of overground running.

Conclusions

The findings of this study suggest that LBPPT may serve as an alternative method of training. This could allow athletes to reach a certain mileage or training volume and reduce cumulative impact forces while maintaining aerobic intensity, which could potentially reduce overuse or mechanical exposure. The findings support the idea that LBPPT allows runners to sustain the same aerobic intensity at 60% VO_{2peak} during a 5-km run while significantly reducing accumulated impact force, despite no change in impact force per step training the muscles to similar loads. This reduction in cumulative force may help reduce the risk of overuse injuries caused by repetitive microtrauma [19] while still exposing the musculoskeletal system to loading patterns comparable to those experienced at 100% BW.

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