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Original Research

The effect of body weight reduction using a lower body positive pressure treadmill on plantar pressure measures while running

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ABSTRACT

Objective: To evaluate the effects of body weight reduction at 10% intervals on pressure distribution variables across regions of the foot while running.
Study design: Crossover Study Design.
Setting: Laboratory.
Participants: 12 recreational runners.
Main outcome measures: Pressure-time integral, peak pressure, instance of peak pressure, contact area, contact time and center of pressure (COP) location at initial contact across four foot regions were measured while participants ran at self-selected speed on the Lower Body Positive Pressure Treadmill (LBPPT) at 100%, 90%, 80%, 70% and 60% of their body weight (%BW).
Results: As the %BW decreased, there were corresponding significant decreases in the pressure-time integral and peak pressures in all four regions of the foot. Significant differences within foot region and %BW for the other variables were infrequent. There was a significant anterior shift of the COP location at initial contact as the %BW decreased.
Conclusion: LBPPT is useful for reducing the pressure across the entire foot. Additionally, the anterior translation of the COP location at initial contact with reduced %BW may provide an additional gait retraining tool for prevention and treatment of running injuries as reducing %BW moves the runner away from a rearfoot strike pattern.

1. Introduction

Lower body positive pressure treadmills (LBPPT) use differential air pressure technology to reduce ground reaction forces and permit unweighting exercise. This technology is especially beneficial for patients who have weight-bearing restrictions such as post-traumatic joint or bone injuries. Also, LBPPT may provide patients, who are returning to walking or running, a quantifiable method of grading the progression of the forces to prevent reinjury or overuse. Among runners, Davis and Futrell (2016) note that the running dosage is one modifiable factor that influences the accumulation of stresses leading to an injury. Whether a patient is simply increasing their training or returning from a lower extremity injury, LBPPT allows the practitioner to alter the loading parameters in order to manage the dosage of cumulative load and ultimately prevent injury. Despite the increasing use of LBPPT in the rehabilitation of injured athletes, the effects on running gait biomechanics at differing clinically relevant magnitudes of unloading remain unclear.

Various studies have reported sizeable and linear decreases in ground reaction forces with unloading of body weight during walking and running in LBPPT(Cutuk et al., 2006; Smoliga, Wirfel, Paul, Doarnberger, & Ford, 2015). The decrease in the actual maximum force experienced during running, however, does not directly correspond to the selected percentage of body weight supported by the runner (%BW). Rather, the selected %BW on a LBPPT actually refers to the force generated by locomotion that exceeds static body weight, and it is the ratio of this additional force supported by the runner in an LBPPT relative to running unsupported. For example, running at a selected 20%BW is equivalent to an approximate 50% decrease of in-shoe forces while running unsupported (Smoliga et al., 2015). Moreover, the distribution of the forces across the plantar aspect of the foot is also not uniformly reduced with changes in supported body weight. Generally, at any

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given %BW reduction, the rear foot has a greater decrease in force compared to the midfoot and forefoot during the stance phase of gait due to a transition toward a forefoot strike at initial contact (Smoliga et al., 2015). Within a given %BW setting, clinicians must be aware of the variability in plantar force in order to prescribe appropriate LBPPT parameters for a given injury.

Previous studies have investigated LBPPT on ground reaction forces and plantar pressures across a relatively wide range of %BW settings(Cutuk et al., 2006; Ruckstuhl, Kho, Weed, Wilkinson, & Hargens, 2009; Smoliga et al., 2015). Smolgi et al. (2015) reported significant differences of in-shoe force and impulse loading at settings spaced at 20% intervals between 20 and 100%BW. However, the influence of smaller %BW settings on ground reaction forces and plantar pressures has not been reported. Given the variable distribution of forces across the foot with changes in %BW, information about load sharing within a more narrow alteration of %BW settings may be beneficial when developing injury specific rehabilitation programs. Additionally, because running programs on LBPPT are typically initiated at middle ranges of %BW (Alter G Protocols, 2020; Warden, Davis, & Fredericson, 2014), we elected to evaluate the range of 60–100% BW. Therefore, the purpose of this study was to evaluate the effects of 10% intervals of body weight reduction, within a clinically relevant range of unloading, during running on plantar pressure load and distribution measures across the rearfoot, midfoot, forefoot and toes.

2. Methods

2.1. Study design

A descriptive laboratory study was performed to analyze the effect of unweighting during treadmill running on measures of plantar pressure in recreational runners. The independent variables were %BW settings of 100%, 90%, 80%, 70%, and 60%BW. The dependent variables were peak pressure, pressure time integral, instance of peak pressure, contact area and contact time of the rearfoot, midfoot, forefoot, and toes as well as the anterior-posterior location of the center of pressure (COP) at initial contact.

2.2. Participants

A convenience sample of 12 recreational runners volunteered for this study (6 males, 6 females; age = 23.2 ± 5.7 years; height 168.7 ± 9.8 cm; body mass 65.9 ± 13.0 kg). To be included in this study, participants had to be able to maintain a 2.7 m/s (6 mph) pace for at least 20 min. All participants were visually observed to have a rearfoot strike pattern during treadmill running by a member of the study team. Participants were excluded if they had any pain (acute or chronic) while running. This study was approved by the university's Institutional Review Board for Health Sciences Research and all participants freely provided written informed consent prior to participation. The rights of the participants were protected.

2.3. Instruments

2.3.1. Plantar pressure

Plantar pressure was measured using the Pedar-x plantar pressure system (Novel Inc, St Paul MN) with in-shoe plantar pressure insoles that had a sampling rate of 100 Hz. Participants used their personal running shoes for all trials. All trials were completed on an unweighting treadmill (G-Trainer™, Alter-G Inc., Menlo Park, CA) (Fig. 1).

Fig. 1. Lower body positive pressure treadmill.

2.4. Procedures

Participants completed a general health history and running questionnaire. Next, in-shoe plantar pressure sensors were placed in the participants' personal running shoes. Participants were then set-up on the unweighting treadmill and asked to self-select their normal running pace that they could easily maintain for a minimum of 20 min. Participants began jogging and progressed to their self-selected running pace (between 2.7 m/s and 4.47 m/s) over a 5-min warm-up and accommodation period. After the self-selected pace was achieved and the subject reported a normal running pattern, baseline (100%BW) data was collected. Plantar pressure data was collected for 45 s at each %BW. After baseline data collection, participants completed the various %BW settings (90%, 80%, 70%, 60%) in a randomized order. In order to account for alterations in plantar pressure due to fatigue, trials were randomized using a Latin square randomization scheme. At each %BW, participants were given a 2-min accommodation period before data was collected. Immediately following the 45 s of data collection, the subject was transitioned to the next %BW setting and a 2 min accommodation period was completed before data collection began. Participants maintained their self-selected running pace for the entire duration of data collection, which lasted for approximately 20 min (5-min warm-up, 45-s baseline data collection, 2-min accommodation and 45-s of data collection at each percentage of body weight).

2.5. Data reduction

2.5.1. Plantar pressure

The mean peak pressure, pressure time integral, instance of peak pressure, contact area and contact time over 10 consecutive steps for each %BW was processed using Novel Database Pro 1/14 and Automask software packages (Novel Inc, St Paul, MN). This was completed for 4 specific regions of the foot (rearfoot, midfoot, forefoot, and toes). Peak pressure represented the highest point of pressure (kPa) in a given region of the foot during stance phase of gait. The pressure-time integral (kPa*s) was defined as the area under the curve of the plantar pressure magnitude during the time spent in stance for each region of the foot. Instance of peak pressure was the percentage of stance when the peak pressure occurred for that specific region. Contact area and contact time indicated how large of an area (cm^2) and how long (ms) each region was in contact with the ground during the stance phase of gait. The anterior-posterior location of the COP at initial contact was measured in millimeters from the most posterior aspect of the rearfoot.

2.6. Statistical analysis

For each dependent variable, a repeated-measures analysis of variance (ANOVA) was utilized to assess the effect of %BW condition on plantar pressure. If there was a significant condition main effect, *post hoc* paired t-tests were then used to identify the specific significant differences between body weight percentages. The level of significance was set *a priori* at $\alpha = 0.05$ for all analyses, and per contemporary statistical recommendations, we chose not to control for multiple comparisons (Hopkins, Marshall, Batterham, & Hanin, 2009). Effect sizes for repeated measures and 95% confidence intervals, as described by Morris and DeShon (2002) were also calculated to compare the magnitude and precision of difference between all weight bearing conditions. Effect sizes were interpreted as > 0.80 was large, 0.50–0.79 was moderate, 0.20–0.49 was small, and <0.20 was trivial.

3. Results

As expected, as the supported %BW decreased, there were corresponding reductions in the pressure-time integral and peak pressures for all four regions of the foot (condition main effect: $P < .001$ for all comparisons). Significant pairwise comparisons and percent change from 100% BW for pressure-time integral and peak pressure can be found in Tables 1 and 2, respectively. Tables 3 and 4 indicate that the magnitude of the changes were significant and moderate to large for most weight bearing conditions in all foot regions for pressure-time integral and peak pressure, respectively.

The instance of peak pressure occurred significantly earlier in the midfoot ($P = .030$), forefoot ($P < .001$), and toes ($P = .002$) as the %BW decreased. There was not a significant main effect for the instance of peak pressure for the rearfoot ($P = .392$). Significant pairwise comparisons and effect sizes for the instance of peak pressure can be found in Tables 5 and 6, respectively.

As the %BW supported by the runner decreased, the contact area of the rearfoot significantly decreased ($P = .007$) (Table 7), but the magnitudes of change were small to moderate and not significant (Table 8). As the %BW decreased, there was a significant and large anterior shift in the location of the COP at initial contact (Table 9). Significant pairwise comparisons ($P < .001$) of the location of the COP at initial contact can be found in Fig. 2. Significantly large changes between the majority of %BW comparisons to 100% BW were identified, and the significant pairwise comparisons and effects sizes are presented in Table 10 and Table 11, respectively.

4. Discussion

The primary results of this study indicate that as %BW was reduced, there were corresponding decreases in plantar pressure measures, specifically pressure-time integral and peak pressure, across all regions of the foot, and COP location at initial contact migrated anteriorly indicating that runners appeared to move from a more rearfoot strike pattern towards a more midfoot or forefoot strike pattern.

LBPPT has much potential as a rehabilitation tool for patients who have weight bearing restrictions or overuse injuries. Patients may maintain similar movement and force distribution patterns during walking or running activity with significantly less force and impulse at foot strike (Sainton et al., 2015). Our results support the similarity of movement and force distribution patterns as contact area and contact time were minimally impacted with progressive % BW changes. However, to return to daily or sport specific activity, practitioners must be able to systematically progress the load on the tissue to stimulate a healing response. Smoliga et al. (2015) statistically modeled the maximum plantar force experienced in LBPPT based on the bw and running speed. Based on this model, statistical equations were derived to permit practitioners to develop a progression of maximum forces that may be patient-specific. Unfortunately, as noted by the authors, the critical threshold for stimulation of tissue healing is unknown, and the progression of forces remain at the discretion of the practitioners' clinical judgment.

A related consideration for the clinician who is advising a progression on a LBPPT is that changes in pressure and the pressure-time integral are not uniform across different regions of the foot. The peak pressure and pressure-time integral are effectively reduced in all regions between most levels of supported %BW. Furthermore, the pressure-time integral are similar between regions while the relative pressure reductions are greater in the rearfoot than the other regions. Smolgia et al. (2015) reported similar findings that among runners using a LBPPT, decreases in % BW resulted in a linear reduction of in-shoe force and impulse that was not uniform across the different regions of the foot. Specifically, larger force decrements were recorded in the rearfoot region as compared to the midfoot and forefoot. Variability in plantar kinetics across the regions of the foot during unweighting in an LBPPT appear substantiated with consideration of the findings of these

Table 1
Pressure-time integral (kiloPascal*millisecond) as a function of percent body weight[a] and % of change from 100% BW with 95% confidence intervals for each foot region.

	100% BW	90% BW	80% BW	70% BW	60% BW
Rearfoot	19.9 ± 2.4 [bcde]	16.7 ± 1.8 [cdef]	15.2 ± 1.6[bdf]	13.6 ± 1.5[bcf]	11.4 ± 1.1[bcf]
		16.2% (13.6%, 18.8%)	23.9% (21.4%, 26.4%)	32.0% (29.5%, 34.4%)	42.7% (40.4%, 45.0%)
Midfoot	26.7 ± 2.8[bcde]	23.0 ± 2.4 [cdef]	21.4 ± 2.4 [bdef]	19.9 ± 2.2 [bcf]	18.1 ± 1.7 [bcf]
		13.9% (11.7%, 16.3%)	19.7% (17.4%, 22.1%)	25.3% (23.0%, 27.6%)	32.4% (30.3%, 34.5%)
Forefoot	35.8 ± 2.2 [bcde]	33.3 ± 1.8 [cdef]	31.6 ± 2.0 [bdef]	29.4 ± 2.0 [bcf]	27.6 ± 1.9 [bcf]
		6.9% (5.5%, 8.2%)	11.9% (10.4%, 13.3%)	17.9% (16.4%, 19.3%)	22.9% (21.5%, 24.3%)
Toes	37.6 ± 2.0 [bcde]	34.2 ± 1.5[def]	32.7 ± 1.7[ef]	31.1 ± 1.8[fb]	29.4 ± 1.8 [bcf]
		8.9% (7.8%, 10.1%)	13.1% (11.9%, 14.3%)	17.3% (16.1%, 18.5%)	21.7% (20.5%, 22.9%)

Abbreviation: %BW, percent body weight.
[a] Values are mean ± SEM.
[b] Significantly different ($P < .05$) from 90%BW.
[c] Significantly different ($P < .05$) from 80% BW.
[d] Significantly different ($P < .05$) from 70% BW.
[e] Significantly different ($P < .05$) from 60% BW.
[f] Significantly different ($P < .05$) from 100% BW.

Table 2
Peak pressure (kiloPascals) as a function of percent body weight[a] and % of change from 100% BW with 95% confidence intervals for each foot region.

	100% BW	90% BW	80% BW	70% BW	60% BW
Rearfoot	189.8 ± 20.3[bcde]	165.0 ± 15.1[ef] 13.1% (5%, 21.1%)	157.6 ± 17.9[ef] 17.0% (8.4%, 25.5%)	145.5 ± 17.0[ef] 23.4% 15.0%, 31.7%)	120.0 ± 14.6[bcdf] 36.8% (28.9%, 44.7%)
Midfoot	172.2 ± 14.3[bcde]	159.3 ± 12.2[cdef] 7.5% (1.0%, 14.1%)	151.9 ± 13.3 [bdef] 11.7% (5.0, 18.6)	141.4 ± 12.7 [bcef] 17.9*% (11.2%, 24.5%)	129.5 ± 10.1 [bcde] 24.8% (18.7%, 30.9%)
Forefoot	240.8 ± 12.5 [de]	237.0 ± 11.0 [cde] 1.6% (−2.6%, 5.7%)	228.4 ± 12.0 [bde] 5.2% (0.8%, 9.4%)	215.4 ± 12.2 [bcf] 10.6% (6.2%, 14.9%)	205.6 ± 12.6 [bcf] 14.6% (10.2%, 19.0%)
Toes	271.7 ± 19.2 [cde]	262.5 ± 15.8[de] 3.4% (−2.1%, 8.8%)	254.0 ± 16.6[f] 6.5% (0.9%, 12.1%)	244.4 ± 18.2[bf] 10.0% (4.2%, 15.8%)	240.7 ± 18.4 [bf] 11.4% (5.5%, 17.2%

Abbreviation: %BW, percent body weight.
[a] Values are mean ± SEM.
[b] Significantly different (P < .05) from 90%BW.
[c] Significantly different (P < .05) from 80% BW.
[d] Significantly different (P < .05) from 70% BW.
[e] Significantly different (P < .05) from 60% BW.
[f] Significantly different (P < .05) from 100% BW.

Table 3
Effect size of %BW versus comparators for pressure*time integral per foot region.

	Rearfoot	Midfoot	Forefoot	Toes
	vs. 100%	vs. 100%	vs. 100%	vs. 100%
90%	1.09 (−0.37, 1.25)	1.58 (0.66, 2.5)	0.99 (0.15, 1.84)	2.04 (1.05, 3.03)
80%	2.64 (1.55, 3.74)	2.56 (1.48, 3.64)	1.45 (0.55, 2.34)	2.45 (1.37, 3.49)
70%	3.12 (1.99, 4.41)	2.76 (1.65, 3.88)	2.90 (1.75, 4.04)	2.10 (1.11, 3.11)
60%	4.58 (3.06, 6.11)	3.73 (2.40, 5.05)	1.57 (0.66, 2.49)	0.74 (−0.08, 1.56)
	vs. 90%	vs. 90%	vs. 90%	vs. 90%
80%	1.10 (0.24, 1.95)	0.92 (0.08, 1.76)	1.05 (0.19, 1.90)	0.67 (−0.15, 1.49)
70%	2.08 (1.09, 3.08)	1.13 (0.27, 1.99)	1.10 (0.24, 1.96)	0.95 (0.10, 1.79)
60%	4.02 (2.63, 5.41)	2.00 (1.02, 2.98)	1.22 (0.35, 2.01)	0.42 (−0.38, 1.23)
	vs. 80%	vs. 80%	vs. 80%	vs. 80%
70%	1.15 (0.28, 2.02)	0.72 (−0.11, 1.54)	0.77 (−0.05, 1.61)	0.68 (−0.14, 1.51)
60%	1.65 (0.71, 2.57)	0.90 (0.06, 1.74)	0.98 (0.3, 1.82)	−0.31 (−0.49, 1.11)
	vs. 70%	vs. 70%	vs. 70%	vs. 70%
60%	2.00 (1.03, 2.99)	0.50 (−0.31, 1.31)	0.44 (−0.37, 1.25)	−0.15 (−0.65, 0.95)

Table 4
Effect size of %BW versus comparators for peak pressure per foot region.

	Rearfoot	Midfoot	Forefoot	Toes
	vs. 100%	vs. 100%	vs. 100%	vs. 100%
90%	0.90 (0.06, 1.73)	0.82 (−0.01, 1.65)	0.25 (−0.56, 1.05)	0.59 (−0.22, 1.41)
80%	1.06 (0.21, 1.91)	1.39 (0.50, 2.28)	0.74 (−0.08, 1.57)	1.09 (0.23, 1.94)
70%	1.78 (0.83, 2.72)	1.76 (0.81, 2.70)	1.73 (0.80, 2.67)	1.16 (0.29, 2.02)
60%	2.19 (1.18, 3.20)	2.16 (1.16, 3.17)	1.11 (0.25, 1.97)	0.99 (0.14, 1.83)
	vs. 90%	vs. 90%	vs. 90%	vs. 90%
80%	0.40 (−0.40, 1.21)	0.73 (−0.10,1.55)	0.84 (0.01, 1.67)	0.60 (−0.21, 1.42)
70%	0.52 (−0.28, 1.33)	1.17 (0.31, 2.03)	1.20 (0.33, 2.07)	1.02 (0.17, 1.87)
60%	1.41 (0.51, 2.31)	2.46 (1.40, 3.52)	1.69 (0.76, 2.62)	0.98 (0.14, 1.83)
	vs. 80%	vs. 80%	vs. 80%	vs. 80%
70%	0.42 (−0.39, 1.23)	1.04 (0.19, 1.90)	1.1 (0.25, 1.96)	0.68 (−0.14, 1.5)
60%	1.52 (0.61, 2.43)	1.48 (0.58, 2.38)	1.22 (0.35, 2.10)	0.58 (−0.24, 1.40)
	vs. 70%	vs. 70%	vs. 70%	vs. 70%
60%	1.03 (0.18, 1.89)	0.87 (−0.03, 1.71)	0.46(-0.35, 1.26)	0.29 (−0.51, 1.10)

two studies.

When developing a LBPPT program for a patient with a specific injury, the practitioner must consider the injured region to unload via %BW reduction and the subsequent shifts in COP location at initial contact, or footstike pattern, during gait. For example, research has found that patellofemoral pain syndrome (PFPS) is the most frequently reported running-related injury (Taunton, 2006) and gait retraining is potentially a method to reduce this pain. Willy et al. (2012) found that by altering running mechanics, such as hip adduction, pelvic drop and hip abduction moment, patellofemoral pain (PFP) was reduced. Additionally, Roper et al. (2016) specifically assessed the effect of footstrike on knee pain. When footstike is

Table 5
Instance of peak pressure (percent of stance phase) for each foot region as a function of percent body weight.[a]

	100% BW	90% BW	80% BW	70% BW	60% BW
Rearfoot	10.8 ± 1.4	10.0 ± 1.1	9.9 ± 0.72	11.1 ± 1.7	12.9 ± 2.3
Midfoot	31.5 ± 2.6[b]	29.9 ± 3.2[b]	27.3 ± 3.7	24.6 ± 3.4 [cd]	26.9 ± 3.1
Forefoot	51.8 ± 1.9[e]	51.9 ± 1.7[e]	50.4 ± 1.7	49.2 ± 2.0	48.7 ± 1.8 [cd]
Toes	58.2 ± 2.0[e]	58.3 ± 1.5[e]	56.8 ± 1.7[e]	56.1 ± 1.2	54.5 ± 1.8 [cdf]

Abbreviation: %BW, percent body weight.
[a] Values are mean ± SEM.
[b] Significantly different ($P < .05$) from 70% BW.
[c] Significantly different ($P < .05$) from 90%BW.
[d] Significantly different ($P < .05$) from 100% BW.
[e] Significantly different ($P < .05$) from 60% BW.
[f] Significantly different ($P < .05$) from 80% BW.

converted from a rearfoot strike to a forefoot strike, knee pain is significantly reduced both immediately post-retraining and at 1 month follow up (Roper et al., 2016). Though the cueing the experimental group received in this study was a verbal command to change footstrike pattern, the forefoot strikers also significantly improved knee abduction post-retraining and at 1 month follow up. The significant pain reduction is likely due to these changes in knee abduction as Kulmala et al. (2013) found that these changes reduced patellofemoral contact force and Roper et al. (2016) found that both patellofemoral contact force and patellofemoral stress trended down with the altered footstrike pattern.

In the current study, as the %BW decreased in the LBPPT, the COP migrated anteriorly toward the forefoot, and consequently, the rearfoot contact surface decreased. Similarly, Smolgia et al. (2015) also reported that with decreasing %BW, the maximum force in the rearfoot was disproportionately less than the rest of the foot regions. This likely indicated a transition from a rearfoot to a forefoot striking pattern with decreased %BW. This unsolicited displacement of the COP makes the LBPPT a potentially effective adjunct for injury prevention and treatment of running injuries, such as PFP, that have been shown to benefit from altered footstrike patterns.

Recently, the literature has strongly advocated for altering movement patterns, specifically footstrike patterns, to prevent and treat running-related injuries. Growing evidence has found that adopting a midfoot and forefoot strike while running reduces the large impact peak of the vertical ground-reaction force that contributes to overuse injuries (Cheung & Davis, 2011; Daoud et al., 2012; Davis & Futrell, 2016). Specifically, Willison et al. (2015) found that patellofemoral joint reaction forces and stress is reduced by approximately 10% when a forefoot strike pattern is adopted. The consequence of such force alterations may be best appreciated by considering that runners who habitually use a rearfoot strike pattern have repetitive stress injuries, including tibial stress syndrome, plantar fasciitis, and patellofemoral pain syndrome, at a rate of about twice that of those habitually utilizing a forefoot strike pattern (Samaan, Rainbow, & Davis, 2014). Therefore, gait re-training to implement a midfoot/forefoot strike is

Table 6
Effect size of %BW versus comparators for instance of peak pressure per foot region.

	Rearfoot	Midfoot	Forefoot	Toes
	vs. 100%	vs. 100%	vs. 100%	vs. 100%
90%	0.13 (−0.67, 0.93)	0.18 (−0.63, 0.98)	0.03 (−0.77, 0.83)	−0.01 (−0.81, 0.79)
80%	0.18 (0.62, 0.98)	0.68 (−0.23, 1.40)	.40 (−0.41, 1.21)	0.45 (−0.36, 1.26)
70%	−0.11 (−0.91, 0.70)	1.02 (0.17, 1.88)	0.6 (−0.21, 1.42)	0.65 (−0.17, 1.47)
60%	−0.49 (−1.30, 0.32)	0.54 (−0.28, 1.35)	1.1 (0.21, 1.92)	1.01 (0.16, 1.86)
	vs. 90%	vs. 90%	vs. 90%	vs. 90%
80%	0.01 (−0.79, 0.81)	0.40 (−0.41, 1.21)	0.35 (−0.45, 1.17)	0.39 (−0.42, 1.19)
70%	−0.22 (−1.02, 0.58)	0.72 (−0.10, 1.54)	0.48 (−0.34, 1.3)	0.42(-0.38, 1.23)
60%	0.05 (−0.75, 0.86)	0.38 (−0.43, 1.18)	0.73 (−0.1, 1.56)	1.08 (0.22, 1.94)
	vs. 80%	vs. 80%	vs. 80%	vs. 80%
70%	−0.50 (−1.31, 0.31)	0.47 (−0.34, 1.28)	0.83 (−0.45, 1.16)	0.18 (−0.62, 0.99)
60%	−1.18 (−2.04, 0.31)	0.03 (−0.76, 0.84)	0.36 (−0.44, 1.17)	0.68 (−0.14, 1.50)
	vs. 70%	vs. 70%	vs. 70%	vs. 70%
60%	−0.27 (−1.07, 0.53)	−0.26 (−1.1, 0.54)	0.08 (−0.73, 0.88)	0.83 (−0.17, 1.48)

Table 7
Contact area (cm^2) as a function of percent body weight[a] and % of change from 100% BW with 95% confidence intervals for each foot region.

	100% BW	90% BW	80% BW	70% BW	60% BW
Rearfoot	40.5 ± 1.7[b]	39.9 ± 1.9[b] 1.5% (−11.8%, 5.3%)	39.2 ± 2.3[b] 3.2% (−1.0%, 7.4%)	38.8 ± 2.4 4.2% (0%, 8.5%)	36.8 ± 2.6[cde] 9.1% (4.5%, 13.8%)
Midfoot	50.8 ± 1.9	50.8 ± 1.8 0% (−3.5%, 2.7%)	50.8 ± 1.8 0% (−3.3%, 2.9%)	50.6 ± 1.8 0% (−3.1%, 3.1%)	50.4 ± 1.8 0% (−2.7%, 3.5%)
Forefoot	40.6 ± 1.5	40.5 ± 1.5 0% (−3.1%, 3.1%)	40.5 ± 1.5 0% (−3.1%, 3.1%)	40.5 ± 1.5 0% (−3.1%, 3.1%)	40.5 ± 1.5 0% (−3.1%, 3.1%)
Toes	28.8 ± 4.7	28.6 ± 4.6 1.0% (−3.2%, 4.5%)	28.7 ± 4.6 0% (−3.5%, 4.2%)	28.7 ± 4.6 0% (−3.5%, 4.2%)	28.7 ± 4.5 0% (−3.4%, 4.1%)

Abbreviation: %BW, percent body weight.
[a] Values are mean ± SEM.
[b] Significantly different ($P < .05$) from 60% BW.
[c] Significantly different ($P < .05$) from 90%BW.
[d] Significantly different ($P < .05$) from 80% BW.
[e] Significantly different ($P < .05$) from 100% BW.

Table 8
Effect size of %BW versus comparators for contact area per foot region.

	Rearfoot	Midfoot	Forefoot	Toes
	vs. 100%	vs. 100%	vs. 100%	vs. 100%
90%	0.63 (−0.18, 1.45)	−0.22 (−0.58, 1.02)	0.00 (−0.80, 0.80)	0.30 (−.50, 1.1)
80%	0.44 (−0.37, 1.25)	−0.11 (−0.69, 0.91)	0.00 (−0.80, 0.80)	0.15 (−0.65, 0.96)
70%	0.49 (−0.32, 1.30)	0.00 (−0.80, 0.80)	0.00 (−0.80, 0.80)	0.15 (−0.65, 0.96)
60%	0.68 (−0.15, 1.50)	0.22 (−0.57, 1.02)	0.00 (−0.80, 0.80)	0.15 (−0.65, 0.96)
	vs. 90%	vs. 90%	vs. 90%	vs. 90%
80%	0.37 (−0.44, 1.17)	0.00 (−0.80, 0.80)	0.00 (−0.80, 0.80)	−0.15 (−0.96, 0.64)
70%	0.42 (−0.39, 1.23)	0.23 (−0.57, 1.03)	0.00 (−0.80, 0.80)	−0.15 (−0.96, 0.64)
60%	0.60 (−0.18, 1.46)	0.45 (−0.36, 1.26)	0.00 (−0.80, 0.80)	−0.15 (−0.96, 0.64)
	vs. 80%	vs. 80%	vs. 80%	vs. 80%
70%	0.36 (−0.44, 1.17)	0.23 (−0.57, 1.03)	0.00 (−0.80, 0.80)	0.00 (−0.8, 0.8)
60%	0.82 (−0.01, 1.65)	0.52 (−0.36, 1,26)	0.00 (−0.80, 0.80)	0.00 (−0.8.0.8)
	vs. 70%	vs. 70%	vs. 70%	vs. 70%
60%	0.58 (−0.24, 1.29)	0.22 (−0.58, 1.03)	0.00 (−0.80, 0.80)	0.00 (−0.8, 0.8)

Table 9
Effect size of %BW versus comparators for center of pressure location at initial contact per foot region.

	COP
	vs. 100%
90%	0.40 (−0.41, 1.21)
80%	0.94 (0.1, 1.79)
70%	1.60 (0.68, 2.52)
60%	1.68 (0.75, 2.61)
	vs. 90%
80%	1.18 (0.39, 2.04)
70%	1.74 (0.80, 2.68)
60%	1.89 (0.93, 2.85)
	vs. 80%
70%	1.46 (0.56, 2.36)
60%	1.57 (0.65, 2.48)
	vs. 70%
60%	1.22 (0.36, 2.10)

often used in the clinical setting when treating patients with lower-extremity injuries.

Various gait re-training techniques have been utilized with varying success to alter such parameters as cadence, stride length and/or foot strike patterns with the goal of minimizing tissue load (Barton et al., 2016). Interventions using technique instructions with verbal and visual cues have successfully caused short-term biomechanical changes (Davis & Futrell, 2016; Samaan et al., 2014; Warne et al., 2014) while other methods of gait retraining including real-time and audible feedback have been utilized with mixed results (Cheung & Davis, 2011; Davis & Futrell, 2016). Based on the findings in the current study, as well as those of Smoliga et al. (2015), the use of LBPPT may be effective in altering foot-strike pattern and thus may provide an extrinsic kinesthetic cue that would assist in the retraining of the motor program. Its addition to other common gait retraining interventions may make the motor pattern more lasting (Winstein, 1991). Our results suggest that to maximize the effect of the LBPPT on movement retraining toward a more anterior foot strike, patients should run at a

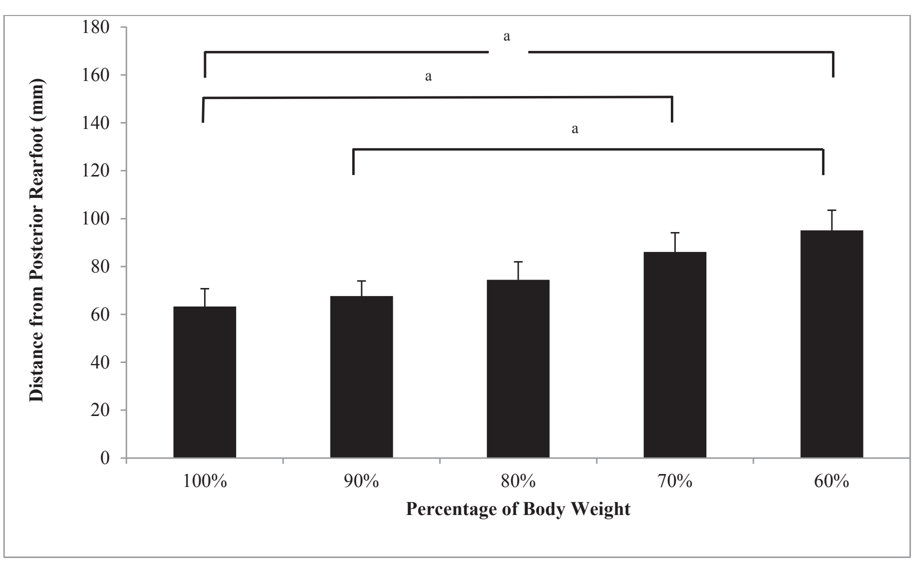

Fig. 2. Means and SEM of the anterior/posterior center of pressure location (millimeters) at initial contact by percent body weight.
[a] Significantly different ($P \leq .05$).

Table 10
Contact time (milliseconds) as a function of percent body weight[a] and % of change from 100% BW with 95% confidence intervals for each foot region.

	100% BW	90% BW	80% BW	70% BW	60% BW
Rearfoot	250.3 ± 24.8 [bc]	220.5 ± 15.6 [bc] 11.9% (4.9%, 18.9%)	214.8 ± 14.4 [d] 14.1% (7.3%, 21.0%)	221.9 ± 23.9 [d] 11.3% (3.1%, 19.6%)	216.9 ± 21.5 13.3% (5.5%, 21.2%)
Midfoot	263.6 ± 20.6	228.1 ± 9.6[c] 13.5% (8.3%, 18.6%	230.4 ± 7.4 12.6% (8.9%, 16.2%)	242.4 ± 18.3 [d] 8.0% (2.8%, 13.3%)	238.2 ± 14.2 9.6% (5.1%, 14.2%)
Forefoot	266.1 ± 19.9 [bc]	235.3 ± 7.3 11.6% (6.8%, 16.3%	230.8 ± 7.3 [d] 13.3% (8.5%, 18.0%)	241.4 ± 18.3 [d] 9.3% (3.2%, 15.4%)	236.7 ± 14.3 11.0% (5.5%, 16.6%)
Toes	263.0 ± 20.3 [bc]	231.7 ± 8.0 11.9% (6.9%, 16.9%)	226.5 ± 8.0 [d] 13.9% (8.9%, 18.8%)	238.4 ± 18.6 [d] 9.4% (3.1%, 15.6%)	231.8 ± 15.3 11.9% 6.1%, 17.6%)

Abbreviation: %BW, percent body weight.
[a] Values are mean ± SEM.
[b] Significantly different (P < .05) from 80% BW.
[c] Significantly different (P < .05) from 70%BW.
[d] Significantly different (P < .05) from 100% BW.

Table 11
Effect size of %BW versus comparators for contact time per foot region.

	Rearfoot	Midfoot	Forefoot	Toes
	vs. 100%	vs. 100%	vs. 100%	vs. 100%
90%	0.61 (−0.22, 1.42)	1.00 (0.16, 1.86)	1.04 (0.19, 1.90)	0.45 (0.22, 1.93)
80%	01.29 (0.41, 2.17)	1.96 (0.98, 2.93)	2.21 (1.19, 3.2)	2.03 (1.05, 3.02)
70%	1.71 (0.787, 2.65)	0.85 (0.01, 1,68)	1.58 (0.67, 2.50)	1.55 (0.63, 2.46)
60%	0.47 (−0.3, 1.28)	0.40 (−0.41, 1.21)	0.47 (−0.35, 1.27)	0.48 (−0.33, 1.29)
	vs. 90%	vs. 90%	vs. 90%	vs. 90%
80%	0.16 (−0.63, 0.96)	0.76 (−0.94, 0.67)	0.18 (−0.62, 0.98)	0.20 (−0.60, 1.00)
70%	−0.02 (−0.82, 0.78)	−0.19 (−1.0, 0.60)	−0.08 (−0.89, 0.72)	−0.09(-0.89, 0.71)
60%	0.05 (−0.75, 0.86)	0.02 (−0.95, 0.65)	−0.02 (−0.82, 0.78)	0.00 (−0.80, 0.80)
	vs. 80%	vs. 80%	vs. 80%	vs. 80%
70%	−0.88 (−1.72, −.05)	−0.24 (−1.04, 0.56)	−0.21 (−1.01, 0.59)	−0.24 (−1.05, 0.56)
60%	0.69 (−0.84, 0.77)	−0.12 (−0.92, 0.68)	−0.09 (−0.89, 0.71)	0.08 (−0.88, 0.72)
	vs. 70%	vs. 70%	vs. 70%	vs. 70%
60%	0.08(-0.73, 0.88)	0.09 (−0.71, 0.88)	0.08 (−0.73, 0.88)	0.10 (−0.70, 0.91)

maximum runner supported body weight of 80% to achieve a significant change in the anterior displacement of the COP location at initial contact. However, at progressively smaller increments of 10% BW changes, the COP location at initial contact moves linearly toward the forefoot. For advanced clinical utility, gradually reloading to 100%BW causes a progressive posterior migration of the COP location at initial contact. Therefore, gradual reloading may be utilized as a method to reduce kinesthetic feedback while the patient works to maintain a more anterior foot strike gait pattern.

Various limitations should be considered when interpreting the results. Although participants were given an opportunity to acclimate to running at each %BW before data collection, variability in weight distribution may have resulted from a lack of familiarity with running on a LBPPT. Additionally, variability in the participants' normal foot strike patterns may have influenced the pressure distribution and the COP migration. This is a relatively small sample size which magnifies the normal variability in pressure distribution and foot strike pattern as represented by the large confidence intervals. Regardless, we were able to identify statistically significant kinetic and kinematic alterations between %BW. Future research should consider the use of wearable sensors such as inertial measurement units that can measure kinetics and kinematics to further elucidate the biomechanical changes that result from running on LBPPT.

5. Conclusion

LBPPT treadmills effectively reduce the peak plantar pressure and pressure-time integral across all regions of the foot. These kinetic changes may be very beneficial during rehabilitation to reduce the stress across tissues of the foot as well as the impact and loading forces of injured tissue in the lower extremity. The COP location at initial contact also migrates anteriorly with lower %BW settings. For running athletes, the anterior shift in COP may be used clinically as a kinesthetic cue to encourage a forefoot strike pattern to further reduce GRF and consequently, the risk of overuse injuries.

Ethical approval

This work has been approved by the Institutional Review Board for Health Sciences Research at the University of Virginia. Subjects gave informed consent to the work.

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Ethical statement

This work has been approved by the Institutional Review Board of Health Sciences Research at the University of Virginia. All Subjects gave informed consent to the work.

Declaration of competing interest

None Declared.

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