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Research article

Oxygen Consumption of Elite Distance Runners on an Anti-Gravity Treadmill®

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Abstract
Lower body positive pressure (LBPP), or 'anti-gravity' treadmills® have become increasingly popular among elite distance runners. However, to date, few studies have assessed the effect of body weight support (BWS) on the metabolic cost of running among elite runners. This study evaluated how BWS influenced the relationship between velocity and metabolic cost among 6 elite male distance runners. Participants ran three- 16 minute tests consisting of 4 stages of 4 minutes at 8, 7, 6 and 5 min·mile^{-1} pace (3.35, 3.84, 4.47 and 5.36 m·s^{-1}), while maintaining an aerobic effort (Respiratory Exchange Ratio ≤1.00). One test was run on a regular treadmill, one on an anti-gravity treadmill with 40% BWS and one with 20% BWS being provided. Expired gas data were collected and regression equations used to determine and compare slopes. Significant decreases in oxygen uptake ($\dot{V}O_2$) were found with each increase in BWS ($p < 0.001$). At 20% BWS, the average decrease in net VO2 was greater than proportional (34%), while at 40% BWS, the average net reduction in VO_2 was close to proportional (38%). Across velocities, the slope of the relationship between VO_2 and velocity ($\Delta\dot{V}O_2/\Delta v$) was steeper with less support. The slopes at both the 20% and 40% BWS conditions were similar, especially when compared to the regular treadmill. Variability in VO_2 between athletes was much greater on the LBPP treadmill and was greater with increased levels of BWS. In this study we evaluated the effect of body weight support on $\dot{V}O_2$ among elite distance runners. We have shown that oxygen uptake decreased with support, but not in direct proportion to that support. Further, because of the high variability in oxygen uptake between athletes on the LBPP treadmill, prediction equations may not be reliable and other indicators (heart rate, perceived exertion or directly measured oxygen uptake) should be used to guide training intensity when training on the LBPP treadmill.

Key words: AlterG®, anti-gravity treadmill®, distance running, elite, oxygen consumption, LBPP treadmill.

Introduction

In recent years, the use of treadmills that provide partial body weight support (BWS) have become increasingly commonplace among elite athletes as a supplemental training and rehabilitation tool. Several technologies for achieving BWS on a treadmill exist, including harness systems, underwater treadmills, and the most recent development, the application of Lower Body Positive Pressure (LBPP). These LBPP treadmill, also called the "Anti-gravity treadmill®", uses positive air pressure applied within a sealed chamber surrounding the subject's pelvis and legs to support the user's body weight. These LBPP treadmills have been used to reduce the ground reaction forces (GRFs) associated with running, while still maintaining a cardiovascular training stimulus via increased treadmill speed (Grabowski and Kram, 2008).

Previous research among non-elite runners has shown oxygen consumption to decrease as BWS is increased using a LBPP treadmill, (Figueroa et al., 2012; Grabowski, 2010; Grabowski and Kram, 2008; Hoffman and Donaghe, 2011; Kline et al., 2015; Raffalt et al., 2013; Ruckstuhl et al., 2010). Furthermore, the percentage reduction in oxygen consumption appears in close proportion to the amount of BWS provided at relatively less supportive conditions, but increasingly less than proportional to the percentage of BWS provided at the more supportive conditions (Grabowski and Kram, 2008; Kline et al., 2015). For example, Grabowski and Kram (2008) reported that with the application of approximately 25%, 50% and 75% BWS, the gross reduction in metabolic power was approximately 25%, 36% and 45%, respectively at a velocity of 3m/s, and 31%, 43%, and 53% at a velocity of 4m/s. Studies have also demonstrated deviation in the actual amount of BWS provided by a LBPP treadmill device when compared to the machine-calibrated levels of support. One paper demonstrated the device to be over-supportive (Hoffman and Donaghe, 2011), while others found the device to be under-supportive, except when the device was inflated and the level of BWS was set to 0% (Grabowski, 2010; Grabowski and Kram, 2008; McNeill et al., 2015). Such deviations may impact interpretation of the relationship between metabolic cost and BWS.

Despite reductions in metabolic cost, it has also been shown that equivalent maximal and sub-maximal oxygen consumption rates (VO_2) can be achieved while running on LBPP treadmills by increasing treadmill velocity to offset the reduction in oxygen consumption associated with running with BWS (Gojanovic et al., 2012; Kline et al., 2015; Raffalt et al., 2013). Studies have also demonstrated linear increases in VO_2 with increases in velocity across a range of BWS conditions, with the slope of the velocity vs VO_2 relationship tending to decrease with increasing BWS (Grabowski and Kram, 2008; Hoffman and Donaghe, 2011; Raffalt et al., 2013). Hoffman and Donaghe (2011) contend that the smaller slope is a product of the effect of speeding up on metabolic demand with increasing BWS.

While these studies provide valuable insight into the metabolic demands of using the LBPP treadmill among recreational athletes, it is not well documented how these findings might apply to the effect of BWS among highly trained runners at the running speeds that

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they use, which are considerably faster than those of recreational runners. Professional athletes pioneered the machine and have recently dominated popular media exposure of the technology, with reports elite athletes use LBPP treadmills for both rehabilitation and training purposes. For example, the first group of professional athletes to use the LBPP treadmill were the long distance runners of the Nike Oregon Project, who used a prototype treadmill in 2005 (www.AlterG®.com). Despite the focus on elite athletes in development and use, current research presents data on the effects of BWS across only a relatively slow and narrow range of velocities that are not applicable to the range of training paces of highly-trained, elite distance runners.

The purpose of the present study was to add data on elite runners to the growing body of literature on LBPP treadmills. Specifically, the goal was to determine the relationship between velocity and metabolic cost while running on an LBPP treadmill, and to examine how the application of BWS affected this relationship. Additionally, due to the highly trained and elite nature of the runners recruited and their ability to comfortably run at relatively fast velocities sub-maximally, we were better able to evaluate the relationship between unloading and metabolic cost at velocities previously unattainable by research subjects without generating significant proportions of energy from non-oxidative pathways. Consistent with the existing LBPP literature, it was hypothesized that 1) as BWS support increased, the metabolic cost associated with running would decrease; 2) this decrease in metabolic cost would be proportionately less than the percentage of BWS provided at greater levels of BWS (i.e. 40% support would lead to less than 40% reduction in VO_2); and 3) the slope of the relationship between BWS and oxygen consumption across velocity would be less steep with greater BWS (indicating that increasing velocity is relatively easier when running with more BWS).

Methods

Six elite male long distance runners (mean age 26.4, SD=4.0 years, mean weight 64.2, SD=4.3 kg) were recruited from the local community of professional and collegiate runners in Flagstaff, Arizona to participate in the study. Inclusion criteria were to have a 5km personal record of less than 14 minutes, a 10km personal record of less than 29 minutes or a half marathon personal record of less than 64 minutes, achieved in the preceding 12 months. All subjects regularly ran on standard running treadmills, and were thus well accommodated to treadmill running (Morgan et al., 1991; 1994; Williams et al., 1991). All participants had also either regularly incorporated LBPP treadmill running into their weekly training using an LBPP treadmill, or had spent at least one hour running on the LBPP treadmill utilized in this study before commencing the study. Previous work by this lab (McNeill et al., 2014) had found that stable VO_2 measurements were achieved after approximately 60 minutes of accommodation to running on the LBPP treadmill; therefore these participants were considered accommodated to LBPP treadmill running. Approval for the protocol was given by the Institutional Review Board of Northern Arizona University, and prior to testing, each participant signed an informed consent.

Protocol and design

The protocol involved two testing days, separated by approximately one week, and not scheduled within 2 days after a hard workout. Testing was done in the morning, and participants consumed the same light, pre-test meal on each of the two testing days, at least one hour beforehand. At the beginning of each testing session, each participant was connected to a metabolic cart (TrueOne 2400, Parvo Medics, Utah, USA) and expired gases were collected for 5 minutes while seated to allow for calculation of the net metabolic rate during treadmill running.

The first testing day involved a 16-minute continuous treadmill run on a regular treadmill (Model ELG, Woodway USA, Inc. Waukesha, WI). This run consisted of 4 stages of 4 minutes each, at paces of 8:00, 7:00, 6:00, and 5:00 minutes-per-mile (3.35, 3.84, 4.47 and 5.36 $m \cdot s^{-1}$), always progressing from slowest to fastest pace.

An LBPP treadmill device (AlterG® Anti-Gravity Treadmill®, AlterG® P200, Fremont, CA) was used for the second testing day. This device utilized an identical treadmill as the one used during the first 16-minute treadmill run (Woodway ELG model, USA, Inc. Waukesha, WI). Both treadmills are calibrated annually. In addition, a manual calibration assessment was conducted at 8.0 miles-per-hour (MPH) (3.58 $m \cdot s^{-1}$ – close to the slowest speed used in the current study) and 12.0 MPH (5.36 $m \cdot s^{-1}$ – the fastest speed used). This was done by multiplying the length of the belt by the number of revolutions per minute (timed and averaged between two timers) to calculate the miles per hour. This assessment showed that the average speed of both treadmills was between 0.016 MPH of each other at 8.0 MPH (8.022 MPH for the non-LBPP Woodway model and 8.038 for the LBPP treadmill) and within 0.030MPH at 12.0 MPH (12.068 MPH on the non-LBPP Woodway and 12.098 MPH for the LBPP treadmill).

In the initial test at 0% BWS, we used the treadmill without LBPP because previous work from our lab has shown that at 0% BWS on the LBPP, the subject was supported to some extent, and we would expect a lower oxygen uptake at an identical speed than on a non-supported treadmill (McNeill et al., 2015). The test involved the same 16-minute continuous treadmill run repeated twice – first with 40% BWS provided, and then with 20% BWS provided, with a recovery period in between. This recovery period lasted at least 45 minutes (off the treadmill) to ensure heart rate returned to resting levels, and the participants felt comfortable and ready to complete the second 16-minute run. For this testing day, participants wore the AlterG® provided neoprene shorts that zip into the AlterG® treadmill enclosure and allow for running in a positive pressure environment. They wore the same shoes for each testing day.

The decision to measure VO_2 with 20% and 40% BWS reflected previous work by this lab (McNeill et al. 2015), which demonstrated the actual amount of BWS provided by a LBPP treadmill to be most accurate when between 10% and 40% BWS was provided. As mentioned, this work also found that the 0% BWS condition on the LBPP treadmill showed a significant deviation and was therefore not included. Instead, the regular treadmill was chosen as the only 0% BWS condition. Second, the choice was further based on evidence that large amounts of BWS may result in more substantial changes in running mechanics (e.g. Raffalt et al., 2013) as well as anecdotal evidence collected from the athletes using our LBPP device that running felt most natural when no more than 40% BWS was provided.

Measurements

Heart rate was monitored throughout each test using a heart rate monitor (FT60, Polar Electro Inc. Lake Success, NY). Participants' rating of perceived exertion (RPE) was determined using the original Borg scale (Borg, 1970) at the end of every two minutes. VO_2 and VCO_2 were measured continuously throughout each test, and the average VO_2 data during the last minute of each four-minute stage was recorded. To ensure the measured VO_2 best accounted for the energy cost of running at each of the four velocities, VO_2 data was only included when the measured Respiratory Exchange Ratio (RER) did not exceed 1.00, indicating a predominantly aerobic effort. Individual regression equations were considered for each of the subjects who had VO_2 measurements associated with an RER > 1.00. If, in those subjects, there was a visually obvious plateau in $\Delta VO_2/\Delta v$ at those velocities with an RER > 1.00, or if the slope of the equation was greatly reduced when the measurement associated with an RER > 1.00 was included, then the VO_2 measured at that velocity was excluded from the analysis.

While running at 5.36 $m{\cdot}s^{-1}$ on the regular treadmill, one participant demonstrated an RER >1.00 (1.03) without any obvious departure of the measured VO_2 at that velocity from the slope of their regression equation, so this value was still included in the analysis. For one participant, improper positioning of the mouthpiece during the test at 40% BWS yielded inaccurate measurements for the first three velocities (3.35, 3.84, and 4.47 $m{\cdot}s^{-1}$) before being fixed, so these measurements were not included in the analysis.

Analyses

To determine whether VO_2 differed significantly across the three test runs, linear mixed model regression analyses were used, comparing VO_2 across all four velocities and three levels of BWS (40%, 20% and regular treadmill). The regression analyses resulted in regression equations predicting VO_2 as a function of both velocity and the amount of BWS provided. To determine the difference in slope between each of the equations, procedures by UCLA Statistical Consulting Group (2014) were followed. These included first creating two dummy coded variables to distinguish the three levels of BWS. Second, interaction terms between velocity and the dummy coded variable were then created. Finally, a regression analysis was used that included the interaction term. If this term was significant, the two slopes were significantly different across those two levels of BWS.

Results

Physiological characteristics

Physiological characteristics of participants across velocity and level of support are summarized in Table 1. Mean gross VO_2 ranged from 23.67 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ at 8 minute·$mile^{-1}$ at 60% of body weight to 59.43 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ at 5 min·$mile^{-1}$ on the regular treadmill. Rating of Perceived Exertion (6-20 scale) and Heart Rate (HR) increased with velocity and was higher with less BWS. RPE ranged from 7.33 (SD = 1.03) at 60% body weight and 8 minute·$mile^{-1}$ to 16.83 (SD = 1.47) on the regular treadmill at 5 minute·$mile^{-1}$ pace. Heart rate ranged from an average of 101.4 (SD = 12.0) at 8 minute·$mile^{-1}$ and 60% body weight to 171.5 (SD = 5.6) at 5 minute·$mile^{-1}$ on the regular treadmill.

Main and interaction effects of BWS and velocity

There was a main effect of velocity $F(df=3) = 129.90$, $p < 0.001$, indicating that VO_2 increased as velocity increased (all p-values <0.001 for comparisons between each velocity). There was also a main effect of BWS, $F(df=2) = 220.02$, $p < 0.001$, showing that VO_2 decreased with each increase in BWS. All levels of BWS were significantly different from each other ($p < 0.001$ for 0% vs. 20% and 40%; whereas 20% vs. 40% BWS was significant with $p = 0.017$). From a proportionality standpoint, with 20% BWS, across all velocities, the average reduction in net $\dot{V}O_2$ was greater than proportional to the amount of BWS (34% reduction in VO_2 for 20% BWS), while at 40% BWS, the average reduction in net $\dot{V}O_2$ was in close proportion to the amount of BWS (38% reduction in VO_2 for 40% BWS).

A significant interaction between BWS and velocity was found $F(df=6) = 3.613$, $p = 0.004$, indicating that the association of velocity and VO_2 may vary across levels of BWS. Post hoc analyses demonstrated that VO_2 did not differ significantly at the three slowest velocities between 20% and 40% BWS (Figure 1).

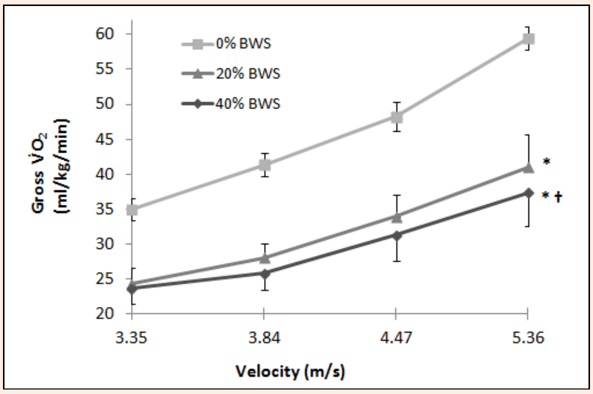

Figure 1. Graph depicting the relationship between gross VO_2 and velocity at each of the three levels of BWS. * indicates a significant difference in the relationship compared with the 0% BWS condition. *† indicates a significant difference in the relationship compared with both the 0% and 20% BWS conditions. At the 20% and 40% BWS conditions, standard deviation bars are shown in only one direction for clarity.

Table 1. Physiologic characteristics of 6 elite distance runners on the AlterG® Anti-Gravity treadmill® by velocity and different levels of body weight support. Data are means (±SD).

Variable	8 min·mile^{-1} (3.35 m·s^{-1})	p[a]	7 min·mile^{-1} (3.84 m·s^{-1})	p	6 min·mile^{-1} (4.47 m·s^{-1})	p	5 min·mile^{-1} (5.36 m·s^{-1})	p
				VO_2 (ml·kg^{-1}·min^{-1})				
0% BWS	35.00 (1.55)		41.35 (1.66)		48.27 (2.03)		59.43 (1.68)	
20% BWS	24.30 (2.29)	<.001	28.05 (2.02)	<.001	33.93 (3.16)	<.001	40.96 (4.73)	<.001
40% BWS	23.67 (2.27)	<.001	25.79 (2.42)	<.001	31.31 (3.76)	<.001	37.37 (4.76)	<.001
Test for 20% vs. 40% BWS		.724		.243		.204		.037
				Net VO_2 (ml·kg^{-1}·min^{-1})				
0% BWS	29.34 (1.85)		35.68 (1.93)		42.60 (1.72)		53.76 (1.51)	
20% BWS	19.29 (1.61)	<.001	23.04 (1.89)	<.001	28.38 (3.03)	<.001	35.96 (4.60)	<.001
40% BWS	18.63 (2.15)	<.001	20.75 (2.28)	<.001	26.28 (3.65)	<.001	32.36 (4.64)	<.001
Test for 20% vs. 40% BWS		.433		.086		.028		.536
				RER (ratio of VCO_2 / VO_2)				
0% BWS	0.85 (0.07)		0.89 (0.05)		0.91 (0.04)		1.00 (0.02)	
20% BWS	0.80 (0.04)	.033	0.88 (0.04)	.478	0.88 (0.03)	.159	0.90 (0.05)	<.001
40% BWS	0.85 (0.06)	.974	0.87 (0.04)	.340	0.87 (0.03)	.097	0.88 (0.03)	<.001
Test for 20% vs. 40% BWS		.045		.779		.746		.471
				HR (Beats Per Min)				
0% BWS	123.4 (6.2)		134.5 (5.3)		151.8 (6.0)		171.5 (5.6)	
20% BWS	105.4 (7.7)	.001	114.5 (8.0)	<.001	126.3 (10.0)	<.001	145.4 (13.7)	<.001
40% BWS	101.4 (12.0)	<.001	107.3 (10.1)	<.001	117.9 (10.6)	<.001	133.9 (12.2)	<.001
Test for 20% vs. 40% BWS		.484		.207		.138		.035
				RPE (6-20)				
0% BWS	9.3 (1.9)		11.7 (2.0)		14.3 (1.4)		16.8 (1.5)	
20% BWS	8.3 (1.2)	.251	10.0 (2.0)	.058	12.3 (1.4)	.024	14.3 (1.2)	.005
40% BWS	7.3 (1.0)	.024	9.2 (1.5)	.005	12.0 (1.3)	.009	14.2 (1.3)	.003
Test for 20% vs. 40% BWS		.251		.338		.700		.847

VO_2 = Oxygen consumption. BWS= Body Weight Support (0% BWS is on regular treadmill); RER= Respiratory Exchange Ratio of VCO_2 to VO_2. HR= Heart Rate; RPE= Rate of perceived Exertion ranging from 6 (very very light to 20= maximum exertion). [a] p-values represent the test for the difference between 0% BWS and 20% BWS, 0% and 40% BWS and the final line represents the test for the difference between 20% and 40% BWS.

Finally, notably, the inter-subject variability was much greater on the LBPP treadmill compared to the regular treadmill for VO_2 and Heart Rate, but not for RER and perceived exertion. For VO_2 on the regular treadmill, the *largest* standard deviation was 4.4% of the mean (at 8min mile pace, 3.35 m·s^{-1}), while the standard deviation on the LBPP treadmill was between 7.2% (at 7 minute·mile^{-1} (3.84 m·s^{-1}) pace at 20% BWS), and 14.3% of the mean (at 5 minute·mile^{-1} pace (5.36 m·s^{-1}) at 40% BWS. Also, the variability in VO_2 (and Heart Rate, but not RPE and RER) tended to increase with velocity on the LBPP treadmill, from 9.5% of the mean at 8 minute·mile^{-1} pace (averaged across 20 and 40% BWS) to 13.6% of the mean at 5 minute·mile^{-1} pace. This was not the case for running on a regular treadmill, where the largest variability was found at the slowest velocity (8 minute·mile^{-1}, SD = 4.4%), and the smallest variability at the fastest velocity (5 minute·mile^{-1}, SD=2.8%). Levene's test of equality of variance showed that the variability at 5 minute·mile^{-1} pace was significantly smaller at 0% BWS compared to 20% BWS ($p = 0.019$) and 40% BWS ($p = 0.019$) (Table 1).

Comparing slopes

Comparison of the velocity vs gross VO_2 relationships at the different levels of BWS showed slopes ($\Delta VO_2 / \Delta v$) of the equations significantly decrease as BWS increases ($p < 0.001$). Equations for the linear regression analyses at each level of BWS are presented in Table 2. With greater BWS, the inter-subject variability increased, as demonstrated by the progressively smaller R^2 values. Additionally, an overall equation, derived from a multiple linear regression analysis, where gross VO_2 was predicted from both BWS and velocity, and which demonstrates a strong positive correlation, is included. As Figure 1 shows, although significantly different, the slopes for the 20% and 40% BWS conditions were more similar than on a regular treadmill without any kind of support.

Table 2. Equations for the graphs depicted in figure 1, as well as an overall equation that uses both the level of BWS and the velocity to predict gross VO_2.

	Regression Equation	R^2
0% BWS	Gross $VO_2 = (12.05*v) - 5.24$	.969
20% BWS	Gross $VO_2 = (8.33*v) - 3.78$	.818
40% BWS	Gross $\dot{V}O_2 = (7.05*v) - 0.45$	.739
Overall	Gross $\dot{V}O_2 = (9.26*v) - (42.18*BWS) + 4.63$	.838

VO_2= Oxygen consumption. BWS= Proportion Body Weight Support (0% BW is on regular treadmill; 20% BWS is 0.20 in the overall formula); R^2=proportion explained variability. v=velocity in meters per second.

Discussion

This is the first study to assess the metabolic demand of running on an LBPP treadmill among elite runners across this wide range of speeds and several different levels of BWS. The first hypothesis, that the metabolic cost of running would decrease as BWS increased, was supported, as there was a significant decrease in metabolic cost across levels of BWS. The finding that the metabolic cost of running decreased with increased BWS has consistently been found in the literature (Figueroa et al., 2012;

Grabowski, 2010; Grabowski and Kram, 2008; Hoffman and Donaghe, 2011; Kline et al., 2015; Raffalt et al., 2013; Ruckstuhl et al., 2010). It has to be noted though, that although there was a main effect for BWS, the difference in metabolic demand between 20% and 40% BWS was small and at the slowest three velocities (3.35 $m \cdot s^{-1}$ through 4.47 $m \cdot s^{-1}$), the pairwise comparisons showed no significant difference. This is further supported by the similarity between the slopes for the 20% and 40% BWS conditions, as compared to the slope while running on a regular treadmill without BWS. Although all three slopes were significantly different from each other, the metabolic requirement on the regular treadmill was markedly higher than both the 20% and 40% BWS runs, even though each condition was separated by equal changes in the percentage of supported body weight (20%).

The second hypothesis – that the decrease in metabolic cost would be attenuated with greater BWS was supported, and can be seen in Figure 1. At 20% BWS, the average reduction in net metabolic cost across all velocities (34%) was more than proportional. But at 40% BWS, the reduction was nearly proportional (38%). When Grabowski and Kram (2008) examined the metabolic cost of running with increments of 25 percent BWS, metabolic cost also decreased to a smaller amount with each successive increase of 25 percent in BWS.

The third hypothesis, that metabolic cost would be decreased to a greater extent at faster velocities with increasing levels of BWS, was supported. As BWS increased from 0% to 20% to 40%, the slopes of the equations of the lines decreased from 12 to 8 to 7 $ml \cdot kg^{-1} \cdot min^{-1}$ per $m \cdot s^{-1}$ indicating that, with greater BWS, the increase in metabolic cost with velocity was blunted. This means it is comparatively easier to "speed up" with increasing levels of BWS, a finding in lines with that of Hoffman & Donaghe (2011). Furthermore, previous work by Kline and colleagues (201) also found a blunted increase in metabolic cost with increasing velocity at higher levels of BWS.

Explanations for the present study's finding can be found in a number of previous pieces of research that have looked at the effects of BWS on the metabolic cost of running. The application of LBPP has a clear role in attenuating the costs associated with supporting body weight vertically during the running gait. But as demonstrated by Grabowski and Kram (2008), LBPP also has a role in providing forward horizontal assistance, and thereby attenuating the concomitant costs of forward propulsion during the running gait. Arellano and Kram (2014) find that body weight support and forward propulsion together account for the vast majority (approximately 80%) of the net metabolic cost of running. Prior research by Chang and Kram (1999) showed that applied horizontal forces were important in reducing metabolic demand among runners, but that there were diminishing returns with greater levels of support. This is consistent with our findings of a diminished reduction in metabolic cost with further BWS being provided. It is possible that in the present study, 20% BWS may constitute an optimal level of applied horizontal support, and that the further small reduction in metabolic demand at 40% BWS may be mostly due to reduced cost of supporting body weight vertically. Grabowski and Kram's (2008) evidence for horizontal assistive forces that increased with increasing velocity may also explain the increased ease of speeding up with BWS found in the present study.

Finally, the increased variability seen in both the 20% and 40% BWS conditions amongst the subjects warrants further discussion. The participants in this study were all highly trained, elite runners. They all have multiple years of training without BWS, and have each developed their most economical stride patterns while running without BWS. Our participants demonstrated remarkable uniformity in running economy at each of the four velocities on the regular treadmill without BWS, as evidenced by a high R^2 value (0.969) seen in Table 1. However, this variability markedly increases when 20% of their body weight was supported ($R^2 = 0.818$) and even further when 40% of their body weight is supported ($R^2 = 0.739$). Despite their "accommodation" to running on an LBPP treadmill, they still demonstrate a much greater variability in the relationship between velocity and metabolic cost. It appears that there is a lack of uniformity in how running economy is affected by BWS.

Beyond the accommodation effect, there may also be a training effect of LBPP running upon running economy. While we ensured each participant had a minimum of one hour accommodation to LBPP running, we did not quantify total training time on the device. Some participants had certainly spent more time on the device than others, which may have exaggerated the differences in running economy while running with BWS compared to without. With different amounts of experience running on the device, it might be important for elite runners to instead gauge workout intensity on other physiological measures, such as a heart rate or rating of perceived exertion when training on an LBPP treadmill. The assumption that the decrease in effective body weight will lead to a proportional decrease in metabolic cost may not be valid. Therefore, runners should not assume that the lowering of weight will have a proportional effect on the change in HR or VO_2, and a direct physiological measurement should be made to assign a cost to the task rather than predicting the cost from the amount of BWS being provided.

Limitations

This study took place at 7,000 ft (2130) altitude. Metabolically, we would not expect differences in the oxygen cost of locomotion at altitude, but we would expect a decrease in the ability of subjects to perform at altitude compared with sea level. Furthermore the participants in this study were all considered to be elite runners, so the relationships between velocity and VO_2, particularly across some of the faster test velocities may not be applicable to the majority of recreational runners. Also, the overall regression equation predicting VO_2 from BWS and velocity was based on a certain range of BWS (20-40% BWS) and speeds (8 $min \cdot mile^{-1}$ through 5 $min \cdot mile^{-1}$) and may not be suitable for different amounts of BWS than used in the current study. Additionally, this was a non-random sample, as these elite runners were specifically recruited. Finally, both Raffalt et al. (2013) and Grabowski and Kram (2008) reported changes in stride kinematics with increasing BWS. This study did not examine the kinematic or kinetic changes that may be associated with BWS running, nor the possible role these changes may play in regards to metabolic cost. Future research is needed to address the mechanism behind the greater variability in economy while running on an LBPP treadmill.

Conclusion

This is the first study to compare the metabolic cost of running on an LBPP treadmill to running on a regular treadmill among elite level distance runners. The results were consistent with prior research, which found that while running on a LBPP treadmill, 1) metabolic cost significantly decreases with increasing levels of BWS, 2) metabolic cost significantly increases with increasing velocity, and 3) there is attenuation in the decrease in metabolic cost as BWS increases. It was also found that there were significant differences in the slopes of the relationship of metabolic cost versus velocity ($\Delta VO_2/\Delta v$) at different levels of BWS, and that the slopes increased as BWS decreased, indicating that body weight support reduced VO_2 more as velocity increased at higher levels of BWS. Finally, variability in the relationship between velocity and metabolic cost increased as the amount of BWS increased.

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Key points

- With increasing amounts of body weight-support (BWS), the slope of the relationship between velocity and oxygen consumption ($\Delta VO_2/\Delta v$) decreases significantly. This means the change in oxygen consumption (VO_2) is significantly smaller over a given change in velocity at higher amounts of BWS.
- There is a non-linear decrease in VO_2 with increasing BWS. As such, with each increment in the amount of BWS provided, the reduction in VO_2 becomes increasingly smaller.
- This paper provides first of its kind data on the effects of BWS on the cost of running among highly trained, elite runners. The outcomes of this study are in line with previous findings among non-elite runners.

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