Maximal Physiological Parameters during Partial Body-Weight Support Treadmill Testing

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ABSTRACT

GOJANOVIC, B., P. CUTTI, R. SHULTZ, and G. O. MATHESON. Maximal Physiological Parameters during Partial Body-Weight Support Treadmill Testing. *Med. Sci. Sports Exerc.*, Vol. 44, No. 10, pp. 1935–1941, 2012. **Purpose**: This study investigated maximal cardiometabolic response while running in a lower body positive pressure treadmill (antigravity treadmill (AG)), which reduces body weight (BW) and impact. The AG is used in rehabilitation of injuries but could have potential for high-speed running, if workload is maximally elevated. **Methods**: Fourteen trained (nine male) runners (age 27 ± 5 yr; 10-km personal best, 38.1 ± 1.1 min) completed a treadmill incremental test (CON) to measure aerobic capacity and heart rate ($\dot{V}O_{2max}$ and HR_{max}). They completed four identical tests (48 h apart, randomized order) on the AG at BW of 100%, 95%, 90%, and 85% (AG100 to AG85). Stride length and rate were measured at peak velocities (V_{peak}). **Results**: $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) was similar across all conditions (men: CON = 66.6 (3.0), AG100 = 65.6 (3.8), AG95 = 65.0 (5.4), AG90 = 65.6 (4.5), and AG85 = 65.0 (4.8); women: CON = 63.0 (4.6), AG100 = 61.4 (4.3), AG95 = 60.7 (4.8), AG90 = 61.4 (3.3), and AG85 = 62.8 (3.9)). Similar results were found for HR_{max}, except for AG85 in men and AG100 and AG90 in women, which were lower than CON. V_{peak} (km·h^{-1}) in men was 19.7 (0.9) in CON, which was lower than every other condition: AG100 = 21.0 (1.9) ($P < 0.05$), AG95 = 21.4 (1.8) ($P < 0.01$), AG90 = 22.3 (2.1) ($P < 0.01$), and AG85 = 22.6 (1.6) ($P < 0.001$). In women, V_{peak} (km·h^{-1}) was similar between CON (17.8 (1.1)) and AG100 (19.3 (1.0)) but higher at AG95 = 19.5 (0.4) ($P < 0.05$), AG90 = 19.5 (0.8) ($P < 0.05$), and AG85 = 21.2 (0.9) ($P < 0.01$). **Conclusions**: The AG can be used at maximal exercise intensities at BW of 85% to 95%, reaching faster running speeds than normally feasible. The AG could be used for overspeed running programs at the highest metabolic response levels. **Key Words:** OVERSPEED, ANTIGRAVITY TREADMILL, LOWER BODY POSITIVE PRESSURE, RUNNING PERFORMANCE, MAXIMAL AEROBIC SPEED, $\dot{V}O_{2max}$

Distance running has generated an extraordinary amount of research, whereas the debate remains open as to what factors contribute most to distance running capacity and which training methods lead to the best effects. To perform at a high level, runners must stay free of injury, and whenever an injury does occur, the ability to come back from it quickly is paramount. Rehabilitation aims to do the following: 1. reduce stress and unload the injured lower body part (diminished impact forces); 2. maintain aerobic training stimulus to minimize fitness losses; 3. not sacrifice too much on specificity of training (as is the case with swimming instead of running). These prerequisites are difficult to meet, and the closest options lie in using body-weight (BW) support techniques such as underwater running or aquajogging. Both techniques involve suboptimal specificity and can potentially alter running kinematics when the runner comes back to overground running.

The antigravity treadmill (AG) by Alter-G™ (Fremont, CA) is a new rehabilitation tool for weight-supported ambulation. This device uses a regular treadmill enclosed in an airtight canopy attached at waist level by "zipping in" using specially designed shorts (Fig. 1). The runner is free to move in all directions with limited horizontal restriction. After calibrated pressurization, positive pressure can be applied to the lower body, effectively "lifting" the runner and reducing BW. Specificity of training is higher, whereas the questions of diminished impact forces and aerobic conditioning have been partially investigated: Grabowski and Kram (11) showed that reduction of BW at a constant running speed of 3 m·s^{-1} decreased ground reaction forces as well as oxygen uptake, although the latter was proportionally less reduced. A few other studies have ascertained the reduction of metabolic cost of ambulation with reduction in BW using AG but never at actual fast training speeds for a runner (10,23). The AG seems to be useful for rehabilitation purposes at reduced BW in injured runners (7,21,25). Another potential use of the AG is when a runner is healthy, trying to actually improve performance with particular training techniques. One particular training technique has been sparsely studied

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FIGURE 1—The lower body positive pressure treadmill (G-trainer AG by Alter-G™).

(in comparison with interval (14,15) or altitude training): overspeed running (19). Specifically, what training adaptations occur when an athlete is forced to run at speeds higher than achievable in normal running? It seems logical to investigate the potential to use overspeed running with endurance runners because part of their training involves high-speed intervals that aim to improve running technique and economy, but also cardiovascular capacity (2). Although the relation between BW reduction in the AG and ground reaction forces remain to be better defined, we are not aware of any data describing cardiometabolic response at maximal running speeds with reduced BW. This knowledge could help optimize use of the AG for performance training in runners. Liefeldt et al. (16) studied elite distance runners as they completed a typical incremental maximal treadmill test, and the same test on a 3% grade downhill, to see whether they could reach maximal oxygen uptake ($\dot{V}O_{2max}$) at faster speeds downhill, which they could not. The authors concluded that some other unidentified factor must have been limiting performance rather than $\dot{V}O_2$, most likely a limitation in muscle recruitment and force generation capacity. Maximal aerobic exercise has been investigated by studies for underwater running, which is the more common way to use BW support for locomotion, and most studies found that maximal metabolic values could not be reached in water (6,26,28).

The AG provides an alternative partial support system that is closer to normal running than any other method available (downhill running [1,20], elastic towing systems [3,4,18], and harness systems [27]). An important unanswered question is whether or not the AG used at various degrees of BW support permits a runner to reach high levels of aerobic stimulation. This study aims to investigate whether distance runners can reach their $\dot{V}O_{2max}$ during a treadmill incremental maximal test at three degrees of BW support, that is, 85%, 90%, and 95% of BW. We hypothesize that they are able to reach their $\dot{V}O_{2max}$ at higher speeds on the AG than on a regular treadmill and at higher leg cadence.

METHODS

Subjects. Fourteen healthy subjects (five women and nine men) voluntarily participated in this study (Table 1). Inclusion criteria targeted local competitive level runners with at least 3 yr of experience and who were actively training at least 15 miles·wk^{-1}. The running ability criteria comprised a recent 10 km in less than 40 min for men and 42 min for women and the absence of recent injuries or medical conditions. Subjects were experienced treadmill users. The study was accepted by the Institutional Review Board of Stanford University and was conducted according to the Declaration of Helsinki. All subjects signed an informed consent.

Experimental procedure. After collection of anthropometrical characteristics, each subject performed a familiarization run on the AG (Alter-G P200, Alter-G™) consisting of 30 min of running at a comfortable pace for at least 5 min at each BW investigated (100%, 95%, 90%, and 85%). At the lowest BW, speed was increased to 19.3 km·h^{-1} (12 mph) for 1 min to get a feel for the faster speeds. A maximal graded running exercise test (GXT) was conducted on a separate day on a regular treadmill (different from the one used for lower body positive pressure but powered by the same Woodway™ technology) at 0% grade (Woodway

TABLE 1. Characteristics of study participants (mean and SD).

	Total (n = 14)		Men (n = 9)		Women (n = 5)		
	Mean	SD	Mean	SD	Mean	SD	*P* Value
Age	27	5.1	27.7	6.3	27	2.1	ns
Height (m)	1.73	0.08	1.77	0.05	1.67	0.06	*
Weight (kg)	69.2	11	76.1	5.3	56.8	6.1	***
BMI (kg·m^{-2})	22.7	2.1	24.2	0.4	20.4	1.5	**
Average miles per week	23.5	7.5	23.1	7.8	24.3	7.8	ns
Years of running experience	10	4.7	9.6	5.4	10.8	3.6	ns
Personal best at 10 km (mm:ss)	38:04	01:22	37:23	01:10	39:18	00:40	***

Statistical differences are all women compared with the men.
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

TABLE 2. Results at maximal phase of test for men and women (mean ± SD).

	HR_{max} (bpm)	V_{peak} (km·h^{-1})	SR_{max} (steps·min^{-1})	SL_{max} (m)	Lactate (mmol·L^{-1})	$\dot{V}_{Emax}$ (L·min^{-1})	BORG breathing	BORG muscular
Men (n = 9)								
CON	190.4 ± 12.8	19.7 ± 0.9	190.2 ± 9.68	1.73 ± 0.11	7.7 ± 2.2	160.9 ± 21.7	8.9 ± 0.7	8.7 ± 1.0
AG100	186.7 ± 9.0	21.0 ± 1.9*	194.2 ± 12.0*	1.79 ± 0.19	7.0 ± 2.6	161.8 ± 20.4	9.3 ± 1.0	9.0 ± 1.4
AG95	185.9 ± 8.4	21.4 ± 1.8**	193.0 ± 11.2*	1.84 ± 0.20*	6.7 ± 1.8	159.8 ± 20.2	9.2 ± 0.9*	9.2 ± 0.8
AG90	186.8 ± 9.2	22.3 ± 2.1**	193.4 ± 9.6**	1.89 ± 0.20**	6.6 ± 2.1	161.5 ± 23.2	9.4 ± 0.5**	8.9 ± 0.9
AG85	184.6 ± 9.1*	22.6 ± 1.6***	194.4 ± 9.0*	1.94 ± 0.16***	6.4 ± 1.8**	159.6 ± 23.4	8.6 ± 0.7	8.8 ± 0.9
Women (n = 5)								
CON	192.2 ± 6.2	17.8 ± 1.1	188.6 ± 12.4	1.61 ± 0.11	7.3 ± 0.9	102.6 ± 2.8	9.3 ± 0.5	8.3 ± 1.0
AG100	189.4 ± 6.1*	19.3 ± 1.0	189.0 ± 13.0	1.71 ± 0.14	8.0 ± 2.8	99.1 ± 10.1	8.8 ± 1.3	9.4 ± 0.6*
AG95	190.0 ± 9.1	19.5 ± 0.4*	189.0 ± 10.8	1.72 ± 0.10*	5.5 ± 1.4	99.9 ± 5.9	8.6 ± 1.1	8.4 ± 0.9
AG90	189.3 ± 8.9*	19.5 ± 0.8*	188.6 ± 11.0	1.77 ± 0.17	6.3 ± 0.7	101.9 ± 4.7	9.0 ± 1.2	8.6 ± 0.8
AG85	189.0 ± 10.3	21.2 ± 0.9**	189.2 ± 11.2	1.88 ± 0.15**	6.4 ± 0.7	101.1 ± 4.6	9.3 ± 0.7	8.7 ± 0.7

Statistical differences are all compared with the baseline "regular treadmill" condition. For $\dot{V}O_2$ values, maximum is reported as highest averaged value over 30 s.
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
HR_{max}, maximal heart rate; SR_{max}, maximal SR; V_{peak}, peak velocity at end of maximal graded exercise test; $\dot{V}_{Emax}$, maximal minute ventilation.

Pro Series; Woodway™ GmbH, Weil am Rhein, Germany). This test determined the benchmark values (CON). The testing protocol started with a 10-min warm-up at 9.7 km·h^{-1} (6 mph), after which, the subject was equipped with the facemask and proceeded with the GXT at 9.7 km·h^{-1} for 1 min. Pace increased by 0.8 km·h^{-1} (0.5 mph) every minute until volitional exhaustion or interruption by the investigators for safety reasons. Capillary lactate was measured at the ear lobe with a portable analyzer that was calibrated before each test (Lactate Pro™; Arkray™, Kyoto, Japan) (13) within the first 30 s after the end of the test. This GXT protocol was repeated on the AG at 100%, 95%, 90%, and 85% BW (AG100, AG95, AG90, and AG85) in randomized order on separate days with at least 48 h between tests, with the exceptions that the starting speed was set two stages higher at 11.3 km·h^{-1} (7 mph), to mitigate the effect of a potential longer test duration. Subjects were blinded to BW support in the AG. Both treadmills have been calibrated before the study started. All tests were conducted between 7 a.m. and 2 p.m., and each subject ran at the same time of day for each test ±1 h.

Outcome measures. The parameters measured were HR_{max} with a thoracic belt and receiver (Polar™ RS800cx; Polar Electro, Kempele, Finland) and expired gas analysis and maximal oxygen uptake ($\dot{V}O_{2max}$), with a metabolic cart (Schiller CS 200 Ergo Spirometer; Schiller Medizintechnik, Ottobrunn, Germany). The gas analysis system was calibrated before each test with ambient air and certified standardized gases. GXT was considered maximal when a plateau in $\dot{V}O_2$ was reached despite an increased work rate or at least two of the following criteria: RER >1.10, HR within 10 beats of predicted maximum (220−age), or lactate ≥8.0 mmol·L^{-1}. $\dot{V}O_{2max}$ was the maximal average value over 10 s. We rated perceived exertion at the end of the GXT (Borg 1–10 scale) and split perceived exertion in two categories: overall exertion (RPE) and peripheral fatigue or leg soreness (RPE_{legs}). We captured video with a high-speed camera (300 Hz) and calculated stride rate (SR) and stride length (SL) with a 2D video analysis software (Silicon Coach™ 7; Silicon Coach Ltd, Dunedin, New Zealand). We analyzed 10 s around the middle point of each stage of the GXT. SR was calculated frame by frame and averaged over 10 cycles. SL was the speed (m·s^{-1}) multiplied by the average stride duration. Intrarater reliability was excellent (Pearson r^2 = 0.99).

Statistical analysis. For each peak test outcome, sex-specific mixed-effects regression models, with a random effect for subject, were used to estimate the effect of AG conditions (AG85, AG90, AG95, and AG100) compared with the normal treadmill (CON) for males and females separately. The submaximal oxygen uptake data were plotted as percentage of maximal oxygen uptake against percentage of maximal aerobic speed ($v\dot{V}O_{2max}$, the minimal speed that elicits $\dot{V}O_{2max}$). Pearson R^2 correlation tests were used to describe the relation between these two parameters for all conditions. All analyses were conducted with R version 9.3 (Team RDC; R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

All 14 participants completed five GXTs. Table 2 presents the main results.

Maximal oxygen uptake, minute ventilation ($\dot{V}_{Emax}$), and time to $\dot{V}O_{2max}$. There was no significant difference found between any of the conditions for all subjects (Fig. 2). The range of averaged $\dot{V}O_{2max}$ for the males was 66.6 ± 3.0 mL·kg^{-1}·min^{-1} (CON) to 65.0 ± 4.8 mL·kg^{-1}·min^{-1} (AG85). The averaged $\dot{V}O_{2max}$ for the females ranged from 63.0 ± 4.6 mL·kg^{-1}·min^{-1} (CON) to 60.7 ± 4.8 mL·kg^{-1}·min^{-1} (AG95). Time to $\dot{V}O_{2max}$ was not different in CON (12.5 ± 1.0 min) compared with AG conditions (12.0 ± 2.5, 12.4 ± 2.2, 13.2 ± 2.7, and 14.1 ± 1.8). There was no significant difference found for $\dot{V}_{Emax}$ between any of the conditions for the men or the women.

Maximal heart rate. For the men, HR_{max} for the AG85 condition (184.6 ± 9.1 bpm) was found to be significantly different (P < 0.05) than the CON condition (190.4 ±

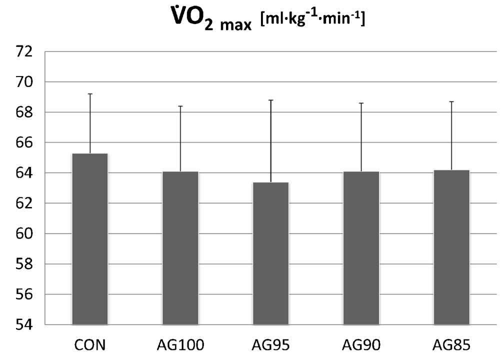

FIGURE 2—Comparison of $\dot{V}O_{2max}$ across different conditions for all 14 subjects (pooled men and women). Data are mean ± SD. No statistically significant differences were present.

12.8 bpm). For the women, the AG100 (189.4 ± 6.1 bpm) and the AG90 (189.3 ± 8.9 bpm) conditions were found to be significantly different ($P < 0.05$) from the CON condition (190.4 ± 12.8 bpm). No other significant differences were found between any conditions.

Peak velocity. V_{peak} in men was 19.7 ± 0.9 km·h^{-1} in CON, which was lower than every other condition: 21.0 ± 1.9 (AG100, $P < 0.05$), 21.4 ± 1.8 (AG95, $P < 0.01$), 22.3 ± 2.1 (AG90, $P < 0.01$), and 22.6 ± 1.6 (AG85, $P < 0.001$). In women, V_{peak} was similar between CON (17.8 ± 1.1) and AG100 (19.3 ± 1.0) but higher in AG95 (19.5 ± 0.4, $P < 0.05$), AG90 (19.5 ± 0.8, $P < 0.05$), and AG85 (21.2 ± 0.9, $P < 0.01$).

SR and SL. In men, SR increased as BW was reduced and V_{peak} increased, with a significant difference for all AG conditions compared with CON ($P < 0.05$). In women, SR did not change. Compared with CON, SL was higher in men for AG95, AG90, and AG85 and higher in women for AG95 and AG85.

Lactate. Lactate at the end of GXT differed only between CON (7.7 ± 2.2 mmol·L^{-1}) and AG85 (6.4 ± 1.8, $P < 0.01$) in men. No other differences were present.

Submaximal oxygen uptake. Figure 3 shows the correlation between %$v\dot{V}O_{2max}$ and %$\dot{V}O_{2max}$; Pearson R^2 values were 0.993 (CON), 0.986 (AG100), 0.999 (AG95), 0.987 (AG90), and 0.994 (AG85).

DISCUSSION

In this study, we measured the maximal physiological and biomechanical running parameters during a typical GXT using a lower body positive pressure treadmill and a regular treadmill. Our hypothesis was that runners would be able to reproduce maximal physiological values ($\dot{V}O_{2max}$ and HR_{max}) from a normal treadmill GXT in all conditions of reduced BW (AG95, AG90, and AG85), albeit with increased speeds. We also hypothesized that an increase in peak velocities would be accompanied by increases in SR and SL. These hypotheses were confirmed by the data, and our results open new perspectives for the use of BW-supported training for athletic purposes. Figure 4 shows an example of metabolic response in all trials in a subject.

Maximal cardiovascular metabolism. Whether BW is not manipulated or is reduced by 5%, 10%, or 15%, local competitive long distance runners present a similar $\dot{V}O_{2max}$ when running in the Alter-G™. It has been reported that devices or techniques that provide some form of assistance to running or weight support do not elicit maximal metabolic stimulation. Mero et al. (18) have shown that when towing forces (elastic pulleys) are applied in sprinters to reach higher speeds, maximal lactate and oxygen uptake are lower than that in regular sprinting. In distance runners, Liefeldt et al. (16). compared regular treadmill testing (to volitional exhaustion) with 3% grade downhill on the treadmill. They observed that runners could not reach their $\dot{V}O_{2max}$ downhill, although they ran faster (23.0 ± 1.0 km·h^{-1} for 0% and 24.6 ± 1.6 for 3%). They concluded that maximal oxygen delivery to muscles could not be responsible for exhaustion in the downhill test, and that other factors were limiting performance such as limited stride frequency, motor unit recruitment, or force generation at high contraction rates because stride frequency was identical in both conditions (only SL accounted for increased peak velocity downhill).

Underwater treadmills are another method of BW-assisted running. Previous studies have investigated maximal metabolic response in deep or shallow water, and results have been conflicting, most finding that it was not possible to reach $\dot{V}O_{2max}$ in the water (6,26,28). Conversely, a recent study by Silvers et al. (24). found equivalent values for underwater compared with land treadmills. Although underwater running can help substitute aerobic exercise while reducing impact forces, there is an issue regarding specificity for runners due to water resistance (8,9).

Heart rate response to maximal exercise in our study is equivalent in men down to AG90 but is significantly lower at AG85 (97% of HR_{max} in CON) and also lower in women at AG95 (99% of CON) and AG85 (98% of CON). In underwater running, lower HR_{max} has been reported but to a higher extent than that in our subjects with values between 86% and 94% of HR_{max} (6,26,28). The slight decrease in

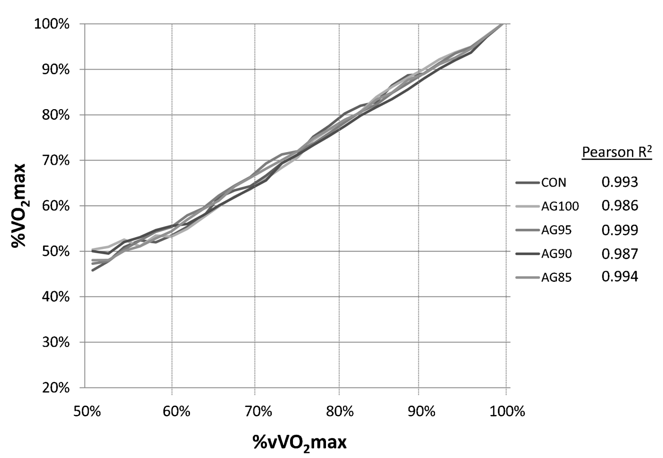

FIGURE 3—Correlation between percentage of maximal aerobic speed (%$v\dot{V}O_{2max}$) and percentage of maximal oxygen uptake (%$\dot{V}O_{2max}$). Data are for all 14 subjects.

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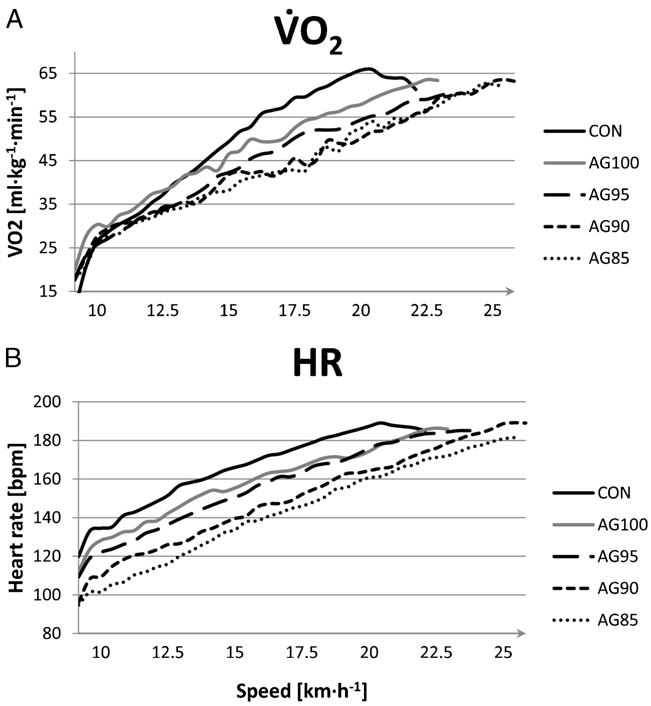

FIGURE 4—Example of oxygen uptake (top) and heart rate (bottom) evolution in the various conditions, data from one subject. CON: normal treadmill, AG100, 95, 90, 85: AG at 100%, 95%, 90%, 85% BW.

HR_{max} that we observe at 85% BW might be linked to a positive effect of lower body positive pressure on venous return, which in turn might be compensated adequately by an increase in stroke volume. Hoffman and Donaghe (12) measured standing HR changes after pressurization to 75% or 50% BW and reported a significant resting HR decrease of 11% (65 to 58 bpm) at 50% BW only. Cutuk et al. (5) examined the cardiovascular response to walking with and without various levels of lower body positive pressure in a similar treadmill system. They observed a reduction in HR with increased amounts of pressure (25 or 50 mm Hg) during walking. It is worth noting that the speed was the same, so the decrease during exercise might have been due to the lesser effort required to move in this modified environment. In our study, the pressure during exercise did not exceed 15 mm Hg, much lower than the pressures of Cutuk et al. Whether tissue pressure explains changes in HR during maximal exercise remains to be investigated, but it does not seem that this limited pressure (<15 mm Hg) would contribute to lowering HR during exercise where the other mechanisms involved in venous return (muscle pump) exert a predominant effect.

Lactate levels at the end of GXTs showed a trend toward lower values than CON in all supported conditions, although only AG85 for men was significant, which may be due to our small sample size. It is an interesting observation, and we cannot directly explain why higher speeds at lower BW would potentially exert less anaerobic stress. In underwater running, Glass et al. (9) observed higher lactate levels than that on ground running, which could be explained by hydrostatic pressure decreasing muscle perfusion, leading to a relative hypoxia and anaerobiosis, a theory supported by Svedenhag and Seger (26). This has been commented by Noakes and St Clair Gibson (22) who state that hypoxia is not present at the muscular level but that the higher lactate levels are due to increased glycolysis and carbohydrate turnover. It could also be that the water resistance to limb movement requires more force generation by lower body muscles, causing more anaerobic resistance-type activity and elevating lactate, which is not the case in the AG.

Biomechanical running parameters. To maintain exercise intensity at reduced BW, our runners were able to compensate by running at faster speeds. The peak velocity V_{peak} increased with higher BW reduction. V_{peak} at AG85 was 15% higher than that in CON for men, and it was 19% higher for women. However, when comparing AG85 to AG100, these differences were smaller, 8% (men) and 10% (women), indicating that the device plays a role in aiding locomotion beyond BW reduction. The lateral stabilization may contribute to lower metabolic cost, allowing runners to reach higher speeds at $\dot{V}O_{2max}$. Nevertheless, the speed differences are still important and of potential significance for performance training. Of the two temporal–spatial determinants of running speed, SR and SL, the latter is predominantly responsible for the increase in velocity with a small contribution of SR in men only: we observe a 12% increase in SL between CON and AG85, whereas SR increases by a mere 2%. The predominance of stride lengthening was previously observed in downhill running (1) and towed sprinters (4,18), although only the fastest sprinters were able to increase both SL and SR to reach faster velocities. The downhill treadmill study by Liefeldt et al. (16) confirmed the same findings. Mero and Komi (17) did observe in sprinters running at supramaximal (towed) speeds a higher contribution of increased SR than SL, pointing to the possibility that training for neuromuscular adaptations could lead to higher leg turnover at similar SL, that is, higher speeds. We have seen limited increases in SR in our male runners (2.2%) and no changes for our female runners. Therefore, it remains unclear whether the AG could be used to improve distance running form. In a recent review, Midgley et al. (19) conclude that overspeed (downhill or with bungee ropes) training had not been appropriately researched yet and call for novel approaches in the field. We believe the AG offers possibilities for runners, especially for overspeed running. This work is a first step in describing physiological and temporal–spatial determinants of running performance using a novel training tool.

Limitations. The percentages of BW support we examined are those indicated by the Alter-G™ treadmill, which we did not verify. Indicated BW reduction by the AG at 75% and 50% was previously reported to be actually 80% and 55%, respectively, (12). Considering performance training, the specificity issue is paramount, and one problem is the aiding lateral support by the machine at hip level. As regards the latter, it is of interest to note that our runners were able to run at faster peak velocities in the AG100 condition compared with CON, which would mean that the apparatus itself provides some aid in running beyond any change in BW. This could be by the decreased cost of vertical or lateral displacement during running, but it remains to be established. Adaptations in SR and SL to prolonged training in the Alter-G™ have not been addressed, because athletes may adapt by increasing step length only, which might be less beneficial. We have established equivalent oxygen uptake response at maximal speeds and have observed a linear relation of the response at lower fractions of the maximal speed, matching the one associated with regular treadmill running, although submaximal responses remain to be investigated during longer bouts at given speeds and BW reductions to obtain steady-state values. One confounding factor could have been the time to attain maximal oxygen uptake, because the subjects reached later and faster stages in the AG. We have chosen to start the tests in the AG two stages later than that in CON to anticipate this potential problem. Although the longest AG tests (AG85) were 1.5 min longer at 14 min, this difference did not reach statistical significance, and we feel that this prolonged exercise duration should not affect the ability to reach highest values of oxygen uptake.

The strengths of our study lie in a homogeneous group of subelite runners. On the basis of our results, we would advise to investigate the potential use for high-speed training in athletes, at 85% to 90% BW, because these settings provide equivalent maximal intensities for $\dot{V}O_2$ and HR along with increases in peak velocity, SR and SL. We would also add to our conclusions the subjective impressions that we have gathered from athletes using the AG in their training or rehabilitation, for whom 85% to 90% BW represents a good range that mixes pain-free running in cases of chronic injuries with a high specificity compared with overground running. Maximal cardiometabolic stimulation can be elicited at these BW settings in the AG as we have shown, and the whole range of exercise intensities can be elicited as well, whether the goal is high-speed training or rehabilitation. This is of clinical significance, and the use of the AG for these purposes could be explored in the future.

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There were no conflicts of interest declared.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. Arakawa K. Biomechanical study on downhill running for sprint training. *Res Rep Kanagawa Inst Tech*. 1993;A17:1–3.
2. Bailey SP, Pate RR. Feasibility of improving running economy. *Sports Med*. 1991;12(4):228–36.
3. Clark DA, Sabick MB, Pfeiffer RP, Kuhlman SM, Knigge NA, Shea KG. Influence of towing force magnitude on the kinematics of supramaximal sprinting. *J Strength Cond Res*. 2009;23(4):1162–8.
4. Corn RJ, Knudson D. Effect of elastic-cord towing on the kinematics of the acceleration phase of sprinting. *J Strength Cond Res*. 2003;17(1):72–5.
5. Cutuk A, Groppo ER, Quigley EJ, White KW, Pedowitz RA, Hargens AR. Ambulation in simulated fractional gravity using lower body positive pressure: cardiovascular safety and gait analyses. *J Appl Physiol*. 2006;101(3):771–7.
6. Dowzer CN, Reilly T, Cable NT, Nevill A. Maximal physiological responses to deep and shallow water running. *Ergonomics*. 1999;42(2):275–81.
7. Eastlack RK, Hargens AR, Groppo ER, Steinbach GC, White KK, Pedowitz RA. Lower body positive-pressure exercise after knee surgery. *Clin Orthop Relat Res*. 2005;431:213–9.
8. Frangolias DD, Rhodes EC. Maximal and ventilatory threshold responses to treadmill and water immersion running. *Med Sci Sports Exerc*. 1995;27(7):1007–13.
9. Glass B, Wilson D, Blessing D, Miller E. A physiological comparison of suspended deep water running to hard surface running. *J Strength Cond Res*. 1995;9(1):17–21.
10. Grabowski AM. Metabolic and biomechanical effects of velocity and weight support using a lower-body positive pressure device during walking. *Arch Phys Med Rehabil*. 2010;91(6):951–7.
11. Grabowski AM, Kram R. Effects of velocity and weight support on ground reaction forces and metabolic power during running. *J Appl Biomech*. 2008;24(3):288–97.
12. Hoffman MD, Donaghe HE. Physiological responses to body weight–supported treadmill exercise in healthy adults. *Arch Phys Med Rehabil*. 2011;92(6):960–6.
13. Howley ET, Bassett DR Jr, Welch HG. Criteria for maximal oxygen uptake: review and commentary. *Med Sci Sports Exerc*. 1995;27(9):1292–301.
14. Kubukeli ZN, Noakes TD, Dennis SC. Training techniques to improve endurance exercise performances. *Sports Med*. 2002;32(8):489–509.
15. Laursen PB, Jenkins DG. The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. *Sports Med*. 2002;32(1):53–73.
16. Liefeldt G, Noakes TD, Dennis SC. Oxygen delivery does not limit peak running speed during incremental downhill running to exhaustion. *Eur J Appl Physiol Occup Physiol*. 1992;64(6):493–6.
17. Mero A, Komi PV. Force–, EMG–, and elasticity–velocity relationships at submaximal, maximal and supramaximal running speeds in sprinters. *Eur J Appl Physiol Occup Physiol*. 1986;55(5):553–61.
18. Mero A, Komi PV, Rusko H, Hirvonen J. Neuromuscular and anaerobic performance of sprinters at maximal and supramaximal speed. *Int J Sports Med*. 1987;8(Suppl 1):55–60.
19. Midgley AW, McNaughton LR, Jones AM. Training to enhance the physiological determinants of long-distance running performance: can valid recommendations be given to runners and coaches based on current scientific knowledge? *Sports Med*. 2007;37(10):857–80.
20. Mizrahi J, Verbitsky O, Isakov E. Shock accelerations and attenuation in downhill and level running. *Clin Biomech (Bristol, Avon)*. 2000;15(1):15–20.
21. Moore MN, Vandenakker-Albanese C, Hoffman MD. Use of partial body-weight support for aggressive return to running after lumbar disk herniation: a case report. *Arch Phys Med Rehabil*. 2010;91(5):803–5.

22. Noakes TD, St Clair Gibson A. Logical limitations to the "catastrophe" models of fatigue during exercise in humans. *Br J Sports Med*. 2004;38(5):648–9.
23. Ruckstuhl H, Schlabs T, Rosales-Velderrain A, Hargens AR. Oxygen consumption during walking and running under fractional weight bearing conditions. *Aviat Space Environ Med*. 2010;81(6):550–4.
24. Silvers WM, Rutledge ER, Dolny DG. Peak cardiorespiratory responses during aquatic and land treadmill exercise. *Med Sci Sports Exerc*. 2007;39(6):969–75.
25. Suchak AA, Bostick GP, Beaupre LA, Durand DC, Jomha NM. The influence of early weight-bearing compared with non–weight-bearing after surgical repair of the Achilles tendon. *J Bone Joint Surg Am*. 2008;90(9):1876–83.
26. Svedenhag J, Seger J. Running on land and in water: comparative exercise physiology. *Med Sci Sports Exerc*. 1992;24(10):1155–60.
27. Teunissen LP, Grabowski A, Kram R. Effects of independently altering body weight and body mass on the metabolic cost of running. *J Exp Biol*. 2007;210(Pt 24):4418–27.
28. Town GP, Bradley SS. Maximal metabolic responses of deep and shallow water running in trained runners. *Med Sci Sports Exerc*. 1991;23(2):238–41.