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Running speed increases plantar load more than per cent body weight on an AlterG® treadmill

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ABSTRACT
AlterG® treadmills allow for running at different speeds as well as at reduced bodyweight (BW), and are used during rehabilitation to reduce the impact load. The aim of this study was to quantify plantar loads borne by the athlete during rehabilitation. Twenty trained male participants ran on the AlterG® treadmill in 36 conditions: all combinations of indicated BW (50–100%) paired with different walking and running speeds (range 6–16 km · hr^{-1}) in a random order. In-shoe maximum plantar force (Fmax) was recorded using the Pedar-X system. Fmax was lowest at the 6 km · hr^{-1} at 50% indicated BW condition at 1.02 ± 0.21BW and peaked at 2.31 ± 0.22BW for the 16 km · hr^{-1} at 100% BW condition. Greater increases in Fmax were seen when increasing running speed while holding per cent BW constant than the reverse (0.74BW–0.91BW increase compared to 0.19–0.31BW). A table is presented with each of the 36 combinations of BW and running speed to allow a more objective progression of plantar loading during rehabilitation. Increasing running speed rather than increasing indicated per cent BW was shown to have the strongest effect on the magnitude of Fmax across the ranges of speeds and indicated per cent BWs examined.

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KEYWORDS
AlterG®; Plantar; Loading; PedarX

Introduction

The concept of optimal loading to maximise healing and remodelling of injured tissues is considered a central tenet of modern sports physiotherapy (Bleakley, Glasgow, & MacAuley, 2012). Manipulation of loading variables can have profound effects on the morphology and mechanical properties of the musculoskeletal system (Glasgow, Phillips, & Bleakley, 2015; Khan & Scott, 2009). Progressive or graduated return to weight-bearing activity is important in the management of many lower limb injuries including stress fractures (Bennell, Matheson, Meeuwisse, & Brukner, 1999; Korpelainen, Orava, Karpakka, Siira, & Hulkko, 2001; Pegrum, Crisp, & Padhiar, 2012), cartilage injury (Mithoefer, Hambly, Della Villa, Silvers, & Mandelbaum, 2009; Mithoefer et al., 2012), ligament injury (Beynnon et al., 2011), muscle injury (Ahmad et al., 2013) and others.

Identification and progression of the optimal level of load is paramount to maximise physiological adaptation while preventing excessive overload (Bleakley et al., 2012; Glasgow et al., 2015; Khan & Scott, 2009). Maximum plantar forces (Fmax), the peak load applied to the plantar surface of the foot during weight-bearing, are a proxy of ground reaction forces (GRFs) borne by the lower limbs. Thus, estimations of these forces during clinically relevant activities can be of use in designing and implementing rehabilitation programmes where graded loading is important (Hreljac, 2004; Willems, Witvrouw, De Cock, & De Clercq, 2007).

Recently, reduced gravity treadmills have become a clinical tool (Gojanovic, Cutti, Shultz, & Matheson, 2012; Saxena & Granot, 2011; Tenforde, Watanabe, Moreno, & Fredericson, 2012). When using reduced gravity treadmills such as the AlterG®, users wear shorts that are zipped into a chamber surrounding the treadmill. By recording both the positive air pressure as well as the weight applied through the deck of the treadmill during a calibration phase, the amount of air pressure required to reduce bodyweight (BW) to varying amounts can be calculated. The amount of reduction in BW commonly used can range from no reduction (100% BW) all the way down to 20% of BW (i.e., extra air pressure added to lift 80% BW off the deck).

Despite more widespread use of AlterG® treadmills in Elite sport and rehabilitation, there is little objective information available for the treating clinician to guide the stages of rehabilitation using this equipment. Smoliga, Wirfel, Paul, Doarnberger, and Ford (2015) examined running speeds ranging from 12.6 km · hr^{-1} to 17.6 km · hr^{-1} and AlterG® indicated BW ranging from 25 to 100% BW (Smoliga et al., 2015). At these combinations, a 1.4% increase in Fmax for every unit increase in BW % was reported. However, those speeds could not examine the transition from walking to running and what effect this may have on Fmax and regional plantar loading.

During over-ground (Kaplan, Barak, Palmonovich, Nyska, & Witvrouw, 2014) and treadmill (Kemozek & Zimmer, 2000) walking and running, it is known that increasing velocity increases plantar loads; however, it is not known what the

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relation is when performing the same progressions in reduced gravity environments. Variation in plantar forces, thus loading for the lower limbs, is considered important for prescription of loading during rehabilitation. The purpose of this study was to quantify the Fmax across a range of clinically relevant speeds and indicated percentage BWs while on a reduced gravity treadmill.

Methods

Particpants

Twenty male experienced runners (age 35.4 ± 7.8 years, weight 77.6 ± 8.4 kg, height 179.1 ± 5.6 cm) volunteered to take part in this study. Runners had to be injury-free for 6 months prior to the study. Informed consent was obtained for each participant, and the experiment was conducted with the approval of the local ethics committee (F2013000001).

Equipment

Plantar loading parameters were measured using a Novel Pedar-X in-shoe system (Novel, Munich, Germany). Each pressure insole is 1.9 mm thick and contains 99 capacitive sensors which were calibrated using a calibration device prior to testing (Trublu Calibration, Novel, Munich, Germany). The insoles relayed data to a Pedar-X data logger that was fixed to the AlterG® treadmill (G-trainer pro 2.0, AlterG®, California USA). Force sensor insoles were placed inside the participants' own preferred running shoes and data were sampled at 100 Hz via Bluetooth. The insole was placed between the sock and shoe with no other manufacturer's insoles or foot orthotics in place so that the Pedar-X insoles were flat (Spooner, Smith, & Kirby, 2010). No participants used orthotic supports.

The validity (McPoil, Cornwall, & Yamada, 1995) and reproducibility (Kemozek & Zimmer, 2000) of the capacitive sensors in the Pedar-X have previously been reported to be excellent. Furthermore, the vertical component of force data obtained by the Pedar in-shoe system correlated well with that obtained by a Kistler force platform with the benefit of being able to capture several footfalls in one trial (Barnett, Cunningham, & West, 2001). Only the vertical component (perpendicular to the insole sensors) of GRF is captured using the Pedar system which may be a limitation when using in-shoe measurement systems compared to force platforms.

Testing protocol

All participants ran for 6 min at 12 km · hr^{-1} (3.3 m · s^{-1}) on an AlterG® treadmill to warm up with no BW assistance (100% BW)(Hardin, van den Bogert, & Hamill, 2004). Thirty-six running trials were each a combination of running speeds from 6 km · hr^{-1} to 16 km · hr^{-1} increasing in 2 km · hr^{-1} increments and indicated BW from 50% BW to 100% indicated BW increasing in 10% increments. Trial conditions were presented in a random order for each participant at each condition. Participants were instructed to run or walk until they felt comfortable, and then indicate the point where their gait felt "normal". Six km · hr^{-1} was chosen as the minimum speed after a pilot investigation showed this to be considered a fast walking speed for all participants, whereas 16 km · hr^{-1} was chosen as a maximum as this was the maximum speed that would be above the aerobic threshold for great majority of recreationally active individuals representing a theoretical 2:40 marathon time. Accordingly, this range of speeds were thought to encompass all speeds typically encountered during rehabilitation: from walking up to relatively fast running.

Statistical analysis

Plantar loading data from the stance phase of six consecutive footfalls were extracted for both the left and right feet and were averaged for subsequent analysis using Novel Pedar-X evaluation software (Groupmask Evaluation, Novel Munich, Germany). The maximum force was normalised to each participant's BW in order to facilitate comparison and was examined for the whole foot for each of the 36 running trials (Girard, Eicher, Fourchet, Micallef, & Millet, 2007). The maximum force data collected by the Pedar-X insoles are reported in units of BW. The indicated BW on the AlterG® treadmill is reported as percentage of BW.

Descriptive and inferential statistics were employed to describe the data using both Microsoft Excel for Windows (Office 2013) and SPSS (version 21.0). Regression analysis was used to describe the relation between peak force and the independent variables of running speed and indicated per cent BW.

Initial comparison was made between left and right foot peak force at each of the 36 trial conditions. After Bonferonni correction for multiple comparison, no statistically significant differences in maximum force were seen between left and right legs. Examination of effect size differences showed a maximum side-to-side difference of 0.22 SD (16 km · hr^{-1} at 70% indicated BW condition; 2.01 ± 0.195BW compared to 1.96 ± 0.191BW for the right and left legs, respectively). No other side-to-side difference exceeded 0.2 SD. Accordingly, data from the left and right legs were pooled for all subsequent analysis.

Results

Maximum plantar force

To examine the effect on maximum plantar force (Fmax) of altering running speed compared to altering indicated per cent BW, regression analyses and descriptive data are presented. Fmax (times BW) for each of the 36 individual trial conditions are presented in Table 1, Figure 1 and Figure 2.

The relation between indicated per cent BW and maximum force was found to be linear at all running speeds (Figure 1), whereas the relation between running speed and Fmax (at all percentages of BW) was best described with a logarithmic curve (Figure 2, Equation (1), adjusted R^2: 0.928). The relative differences in Fmax were seen to be greatest when increasing speed from 6 to 16 km · hr^{-1} while holding indicated per cent BW constant (range: 0.74BW– 0.91BW increase) whereas increasing indicated per cent BW from 50% to 100% showed a smaller increase in peak force (range 0.19BW– 0.31BW) (Table 2).

Table 1. Maximum plantar force (BW multiples (SD)) at the different combinations of indicated percentage BW (50–100%), and speed of running/walking (km · hr^{-1}).

Speed \ Bodyweight	50%	60%	70%	80%	90%	100%
6 km/hr	1.0170 [.2095]	1.0260 [.2080]	1.0670 [.1865]	1.1440 [.1830]	1.1775 [.1780]	1.2095 [.1900]
8 km/hr	1.3675 [.2350]	1.4230 [.2580]	1.4945 [.2290]	1.5380 [.2245]	1.6570 [.2685]	1.7160 [.2415]
10 km/hr	1.5585 [.2255]	1.6940 [.2160]	1.7695 [.2045]	1.8880 [.2165]	1.9785 [.2290]	2.0115 [.2230]
12 km/hr	1.6415 [.2070]	1.8010 [.2150]	1.8775 [.2075]	1.9845 [.2205]	2.1095 [.2130]	2.1475 [.2240]
14 km/hr	1.6925 [.2405]	1.8195 [.1855]	1.9560 [.1995]	2.0770 [.2180]	2.1875 [.2365]	2.2495 [.2240]
16 km/hr	1.7665 [.2085]	1.8715 [.1950]	1.9860 [.1930]	2.1140 [.2085]	2.2230 [.2240]	2.3090 [.2195]

1.0170	Minimum
1.6630	
1.8783	
1.9860	
2.0506	
2.0937	
2.3090	Maximum

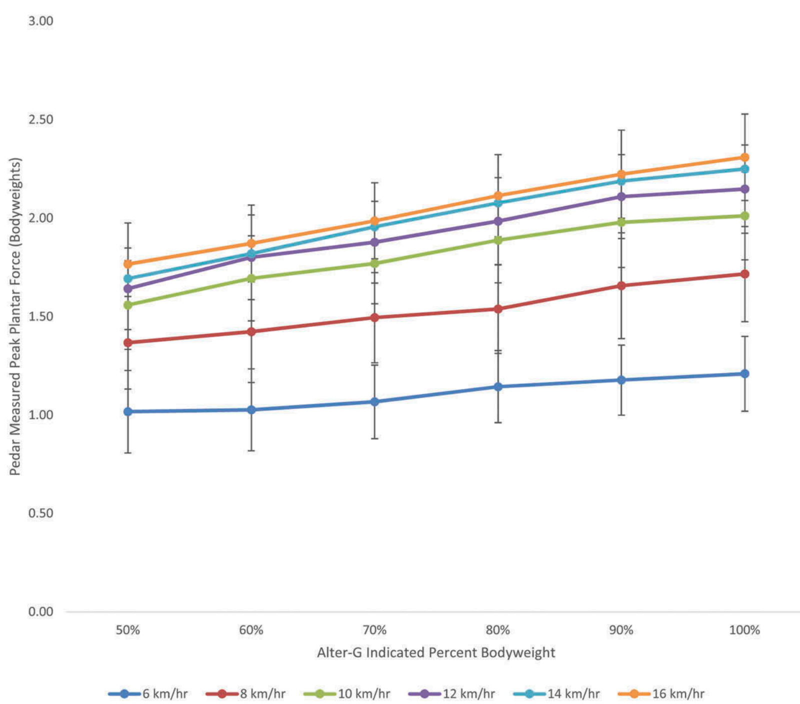

Figure 1. Maximum plantar force at each of the different indicated per cent BW and running speed combinations.

$$Maximum\ Plantar\ Force = 0.42 \cdot Indicated\ Bodyweight + 0.7766 \cdot Ln\ (Speed) - .4037 \quad (1)$$

Equation (1): Regression equation describing the relation between Maximum Plantar Force (in multiples of BW), Indicated BW (percentage) and running speed (in km · hr^{-1}), $P < 0.01$, $R^2 = 0.95$, Adjusted $R^2 = 0.93$.

Contact time

Walking and running speed had the largest effect on contact time rather than altering BW on the AlterG® treadmill. Contact time for the whole foot decreased as running speed increased. Longest contact time was 572.85 ± 75.55 ms for the 100% indicated BW at 6 km · hr^{-1} trial. Shortest contact time was 186.65 ± 23.70 ms for the 50% indicated BW and 16 km · hr^{-1} trial. Altering indicated BW had a much smaller effect on

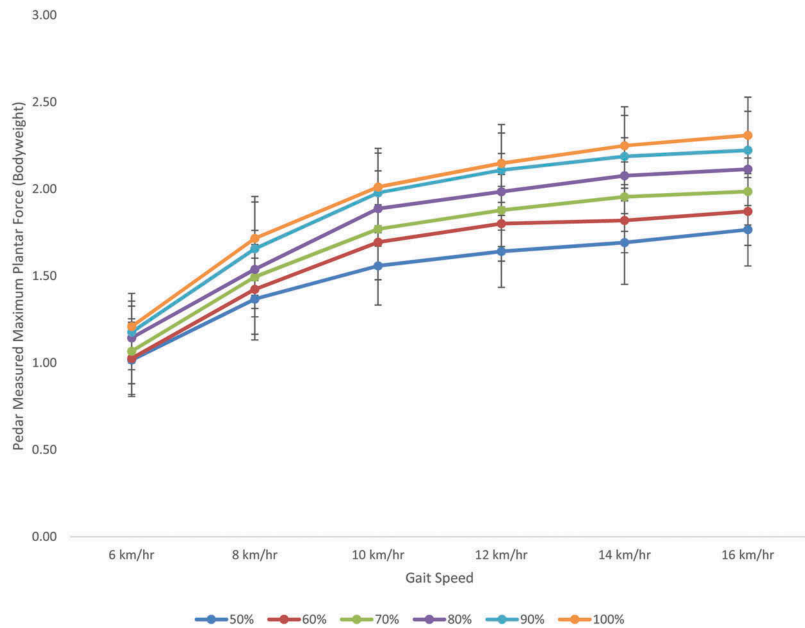

Figure 2. Maximum plantar force at each of the different combinations of running speed and indicated AlterG® % BW.

Table 2. Relative change in maximum force (compared to the maximum observed) for both running speed and per cent BW. For example, when considering the 6 km · h^{-1} condition, there was a change of 0.189BW when moving from 50% indicated BW to 100% indicated BW. Conversely, at the 50% indicated BW condition, there was an increase of 0.737BW when moving from 6 km · hr^{-1} to 16 km · hr^{-1}. In all cases, increasing running speed across a range of indicated BW resulted in a much larger increase in force compared to increasing indicated percentage BW.

Relative change between 50% and 100% indicated Alter-G bodyweight		Relative change between 6km/hr and 16km/hr	
At 6 km/hr	0.189	At 50%	0.737
At 8 km/hr	0.255	At 60%	0.824
At 10 km/hr	0.291	At 70%	0.861
At 12 km/hr	0.308	At 80%	0.848
At 14 km/hr	0.329	At 90%	0.888
At 16 km/hr	0.307	At 100%	0.909

contact time. A table documenting contact times for all 36 combinations of indicated BW and running speed is provided as a supplemental data.

Discussion

Increasing gait speed resulted in larger increments of Fmax for the total foot than increases of indicated per cent BW in the ranges examined here. For example, the increase in Fmax seen across the range of indicated per cent BWs (50–100%) increased by as little as 0.19BW (6 km · hr^{-1} condition) from 1.02BW to 1.21BW to a maximum of 0.54BW (for the 14 km · hr^{-1} condition) from 1.70BW to 2.25BW. Increasing gait speed however had a much larger effect – a minimum of 0.75BW increase at 50% indicated BW (from 1.02BW at 6 km · hr^{-1} up to 1.77BW at 16 km · hr^{-1}) to a maximum of 1.10BW increase in the 100% indicated BW condition (1.21BW at 6 km · hr^{-1} up to 2.31BW at 16 km · hr^{-1}).

Clinicians can use Table 1 to estimate increases in Fmax for their injured athletes as they progress their rehabilitation on an AlterG® treadmill. It can be seen that the initial increases when walking from 1.02BW up to 1.21BW occur by stepping the indicated per cent BW from 50% to 100%, and then the next smallest step to 1.37BW occurs back at 50% of indicated BW, at 8 km · hr^{-1}. Table 1 can then be used to progressively increase either running speed or per cent BW while considering the Fmax. It is suggested that such steps in loading, married up with clinical findings can result in a more systematic approach to return to sport and other running activities.

We had initially suspected that moving from 50% indicated BW to 100% indicated BW would result in an approximate doubling of the peak plantar forces across all running speeds. The data, however, showed the Fmax to increase by as little as 0.19BW to a maximum of 0.31BW. Moreover, in the 50% indicated BW condition, participants were experiencing a minimum of 1BW in peak plantar force at all speeds examined. If it were important to reduce Fmax to less than 1BW, even lower indicated BW or slower gait speeds would be required most likely.

These findings are in accordance with the work of Grabowski and Kram (Grabowski & Kram, 2008) who documented active peak loads between 0.98BW and 2.38BW with participants running between 10.8 km · hr^{-1} and 18.0 km · hr^{-1}. However, this data contrasts with the work of Raper et al. who examined tibial loads using a surface-mounted accelerometer, and considered running speeds from 10 km · hr^{-1} to 20 km · hr^{-1} (Raper et al., 2014). We make several suggestions for this apparent discrepancy. First, the impact force measured with a surface-placed accelerometer on the tibia will likely provide a different reading than a plantar reading from the Pedar-X in-shoe measurement equipment used here. Further, there is the likelihood that some dampening of the force occurs at the foot and ankle, resulting in different forces experienced at the tibia. Finally, we note that, moving from 6 km · hr^{-1} to 8 km · hr^{-1} saw the largest relative and absolute increases in Fmax, with the second largest peaks occurring when stepping from 8 km · hr^{-1} to 10 km · hr^{-1}. These slower speeds were not examined in the study conducted by Raper et al. (Raper et al., 2014).

Speeds between 6 km · hr^{-1} and 10 km · hr^{-1} represent a transition from walking to running in which several kinetic, kinematic and physiological changes occur. During walking, there are two periods within the stance phase of gait in which double-support occurs whereby both feet are in contact with the surface. As gait speed progresses to running there are no periods when both feet are in contact with the ground, meaning a single foot will deal with the GRF and impulse associated with footstrike (Novacheck, 1998). Contact time gradually decreased as speed increased. All participants walked at the 6 km · hr^{-1} speed in which contact time was 579.15 ± 75.55 ms for the 100% indicated BW condition. All participants ran at the 10 km · hr^{-1} speed in which contact time was 264.55 ± 33.50 ms for the 100% indicated BW condition. The 8 km · hr^{-1} trials at various indicated BW represented a transition from walking to running for participants (Table 1, supplemental data). AlterG® indicated BW had little effect on contact time. For example, at 16 km · hr^{-1} contact time was 186.65 ± 23.70 ms for the 50% indicated BW and 193.6 ± 17.80 ms for the 100% indicated BW conditions (supplemental data).

These findings are in accordance with contact times from a recent study by Ribeiro et al. in which a control group of 30 participants ran over-ground at 12 km · hr^{-1} and 100% BW and recorded contact time of 234 ± 21.30 ms. Our findings concur with contact time of 235.40 ± 30.45 ms for the 12 km · hr^{-1} at 100% indicated BW condition on the AlterG® treadmill (Ribeiro, Joao, Dinato, Tessutti, & Sacco, 2015).

Fmax is a measure of in-shoe force experienced at the plantar surface of the foot. The relationship with forces experienced in other joints of the lower limb is complex. Recent work calculating joint torques while over-ground running at 8, 12 and 16 km · hr^{-1} suggests that the peak torques increased both at the ankle and knee at the higher speeds, with greater increases at the ankle (compared to the knee) (Petersen, Nielsen, Rasmussen, & Sorensen, 2014). Similar to the work done here, a larger relative and absolute increase was seen in the step from 8 to 12 km · hr^{-1} compared to the step from 12 to 16 km · hr^{-1}.

Patil et al. measured *in vivo* forces at the knee using a custom tibial prostheses in four elderly participants while they walked on an AlterG® treadmill at speeds ranging from 2.41 to 7.24 km · hr^{-1} and indicated BWs ranging from 25 to 100% BW (Patil et al., 2013). Tibiofemoral force peaked at 5.1 times BW for the 7.24 km · hr^{-1} at 100% indicated BW trial. Lowest force recorded was 0.8 times BW for the 2.41 km · hr^{-1} at 25% indicated BW trial. It is important to note that these forces at the knee are a measure of not only the external GRF during stance phase of the gait cycle but also the muscle force production that occurs in anticipation for or response to interaction with the surface.

The data presented here for Fmax can be used in conjunction with the contact times table (supplemental data) and knowledge of the relations between the load sharing through the lower limb during gait to plan a staged rehabilitation process. However, an individual's response to loading will of course be subject specific and it is suggested that clinical reasoning be used by the clinician in an attempt to find optimal load to expedite rehabilitation from injury.

There are a number of limitations to this study. A potential limitation is the collection frequency of 100 Hz which could result in the loss of true peak value for Fmax. In-shoe force measurement gives the vertical component of GRF only and therefore does not capture medial-lateral of "shear" force that may be important components when considering lower extremity injury (Tessutti, Ribeiro, Trombini-Souza, & Sacco, 2012). Caution should be exercised when comparing these Fmax plantar loads from AlterG® treadmill running to over-ground running as it is known that loads increase with over-ground running and this may result in an under-estimation of Fmax at the given running speeds (Hong, Wang, Li, & Zhou, 2012). Finally, this study was conducted in healthy adult male participants wearing their preferred footwear; it is unknown if the findings would be replicated in injured participants, women or children where gait parameters will likely vary.

Conclusions

Data are presented allowing an evidence-informed graduated return to loading on a reduced gravity treadmill – clinicians can use the tables or regression formula to estimate peak plantar forces for different combinations of running speed (from 6 to 16 km · hr^{-1}) and per cent indicated BW (from 50% to 100%). Increasing running speed, rather than increasing indicated per cent BW, was shown to have the strongest effect on the magnitude of peak plantar forces across the ranges of speeds and indicated per cent BWs examined.

Practical implications

- Faster running speeds (up to 16km · hr^{-1}) caused greater maximum plantar force than increases in per cent BW (up to 100%) on the AlterG® treadmill in healthy male runners for the speeds and BWs tested.
- Table 1 can be used as a guide to allow clinicians to more objectively progress plantar loading during rehabilitation on the AlterG® treadmill for different BW and running speed combinations.
- To reduce plantar loading to below 1 BW in the early stages of rehabilitation it may be necessary to walk at below 6 km · h^{-1} and 50% indicated BW, which was the slowest speed and BW combination used here.

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