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Original article

Stride length–velocity relationship during running with body weight support

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Abstract

Background: Lower body positive pressure (LBPP) treadmills can be used in rehabilitation programs and/or to supplement run mileage in healthy runners by reducing the effective body weight and impact associated with running. The purpose of this study is to determine if body weight support influences the stride length (SL)–velocity as well as leg impact acceleration relationship during running.

Methods: Subjects ($n = 10$, 21.4 ± 2.0 years, 72.4 ± 10.3 kg, 1.76 ± 0.09 m) completed 16 run conditions consisting of specific body weight support and velocity combinations. Velocities tested were 100%, 110%, 120%, and 130% of the preferred velocity (2.75 ± 0.36 m/s). Body weight support conditions consisted of 0, 60%, 70%, and 80% body weight support. SL and leg impact accelerations were determined using a light-weight accelerometer mounted on the surface of the anterior-distal aspect of the tibia. A 4×4 (velocity $\times$ body weight support) repeated measures ANOVA was used for each dependent variable ($\alpha = 0.05$).

Results: Neither SL nor leg impact acceleration were influenced by the interaction of body weight support and velocity ($p > 0.05$). SL was least during no body weight support ($p < 0.05$) but not different between 60%, 70%, and 80% support ($p > 0.05$). Leg impact acceleration was greatest during no body weight support ($p < 0.05$) but not different between 60%, 70%, and 80% support ($p > 0.05$). SL and leg impact accelerations increased with velocity regardless of support ($p < 0.05$).

Conclusion: The relationships between SL and leg impact accelerations with velocity were not influenced by body weight support.

Keywords: Overuse injury; Rehabilitation; Running economy; Stride length–speed

1. Introduction

A lower body positive pressure (LBPP) treadmill uses air pressure in a way that an upward directed force is applied to the user, effectively reducing body weight.[1–8] There is a growing body of research on the biomechanics and physiological response during running at reduced body weight via an LBPP treadmill. For example, it is known that as body weight support increases, ground reaction forces,[3,5,8] metabolic cost,[2,8] and lower extremity muscle activity (in general)[4,6,7] decrease.

Running velocity (m/s) is the product of stride length (SL) (m/stride) and stride frequency (strides/s), and it follows that there is a wealth of information on these parameters during running. For example, it is known that changes in SL more so than stride frequency are closely related to changes in running submaximal velocity[9–11] such that, in general, SL increases as velocity increases.[9–11] Likewise, there is a link between SL and impact characteristics such that the longer the stride the greater the impact.[9,11,12]

Despite the wealth of knowledge on SL and stride frequency, there are only limited data on SL or stride frequency during running with body weight support. Raffalt et al.[8] reported the SL increased as body weight support increased from 0 to 25%, 50%, and 75% support as well as with increasing running velocities (from 2.8 m/s to 6.1 m/s). Gojanovic et al.[2] also reported that SL increased as body weight support increased from 0 to 5%, 10%, and 15% levels of support during a maximal effort graded exercise test (velocities starting at 2.7 m/s). However, there is still a need for more information on these basic kinematic descriptors since the data are limited to elite runners running at high speeds[8] and during maximal

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effort.[2] Information about the SL–velocity (or stride frequency–velocity) relationship during body weight support running at velocities that runners would self-select (*vs*. a prescribed velocity or at maximal velocity) as well as other body weight support levels is important because it gives insight into preferred gait pattern of a runner during submaximal effort—which would be likely used during a rehabilitation program, for example.

Ultimately, how body weight support influences gait patterns may influence decisions about magnitude of body weight support and treadmill speed to use during rehabilitation. Therefore, the purpose of this study was to determine if body weight support influences the SL–velocity relationship during running with an emphasis on high levels of body weight support. Additionally, since impact characteristics may be a risk factor for running overuse injuries,[13] the purpose was to determine if impact characteristics are influenced by body weight support and velocity by measuring leg impact accelerations. It was hypothesized that SL and impact acceleration would increase across velocities at each body weight support level. It was also hypothesized that SL would increase and leg impact accelerations decrease with increases in body weight support.

2. Methods

2.1. Subjects

Ten subjects (4 males, 6 females: 21.4 ± 2.0 years, 72.4 ± 10.3 kg, 1.76 ± 0.09 m) volunteered to participate in this study and gave written informed consent. All subjects were physically active and were comfortable running on the treadmill. All subjects completed all conditions and were free from injury that would interfere in any way with the ability to run on a treadmill. The study was approved by the Institutional Review Board of the host institution.

2.2. Instruments

An LBPP was used for all running conditions (Version 1.20, model: G-Trainer Pro; Alter-G, Inc., Fremont, CA, USA) and subjects were given time to practice using the treadmill prior to testing. To measure SL and leg impact acceleration, an accelerometer (model: 352C67, PCB Piezotronics, Depew, NY, USA) was secured on the surface of the skin at the anterior-distal medial aspect of the tibia. The sensitive axis of the accelerometer was aligned parallel to the long axis of the tibia and held tight to the surface of the skin using an elastic wrap.

2.3. Procedures

After being set up in the LBPP treadmill, subjects performed a self-directed warm-up for up to 10 min that included having subjects run at a variety of body weight support levels. After warm-up, preferred velocity was determined by having the subject self-select a velocity that he/she felt could be maintained for 30 min. The velocity display was hidden from view and the researcher increased/decreased velocity based upon subject feedback. Once the subject selected a velocity, that velocity was recorded and the treadmill was stopped and the process repeated for a total of three times. The test velocity was the average of the three trials and is referred to herein as the preferred velocity.

Subjects completed a total of 16 different running conditions consisting of specific velocity and body weight support combinations. Running velocities tested were 100%, 110%, 120%, and 130% of the preferred velocity. Body weight support conditions consisted of 0, 60%, 70%, and 80% body weight support (i.e., effective weight of 100%, 40%, 30%, and 20% of body weight). Order of conditions was always from slow to fast velocity and in order of increasing body weight support.

Leg acceleration data were collected for 20 s (sample rate: 1000 Hz). Each condition lasted at least 1 min in order to allow an acclimation period (at least 30 s) and a recording period.

2.4. Data reduction

A custom MATLAB program (Version R2010b; MathWorks, Natick, MA, USA) was written to identify 11 consecutive leg impact peak accelerations (leg impact acceleration). Stride frequency was calculated as the inverse of the time between consecutive impact peaks (i.e., 1/stride time, units: Hz). SL (m/stride) was calculated by dividing velocity (m/s) by stride frequency (Hz). For each condition, the 10 SLs and 11 impact accelerations were averaged to represent that condition for each subject. That average value per subject-condition was then used for analysis.

2.5. Statistical analysis

The independent variables in this study were body weight support and velocity. Each dependent variable (SL, leg impact acceleration) was compared across conditions using a 4 (velocity: 100%, 110%, 120%, 130% of preferred velocity) × 4 (body weight support: 0, 60%, 70%, 80% of body weight) repeated measures analysis of variance ($\alpha = 0.05$). If there was a significant interaction between velocity and body weight support, Bonferroni *post hoc* test was used.

3. Results

SL was not influenced by the interaction of body weight support and velocity (Fig. 1A; $F(9, 72) = 1.6$, $p = 0.130$). SL was influenced by body weight support ($F(3, 24) = 21.2$, $p < 0.001$) with SL being shortest during no body weight support ($p < 0.05$) but not different between 80%, 70%, and 60% body weight support levels ($p > 0.05$). SL was influenced by velocity ($F(3, 24) = 115.6$, $p < 0.001$) such that as velocity increased, SL increased regardless of body weight support.

Leg impact acceleration was not influenced by the interaction of velocity and body weight support (Fig. 1B; $F(9, 72) = 1.6$, $p = 0.296$). Leg impact was influenced by body weight support ($F(3, 24) = 6.0$, $p < 0.001$) with leg impact being greatest during no body weight support ($p < 0.05$) but not different between 80%, 70%, and 60% body weight support

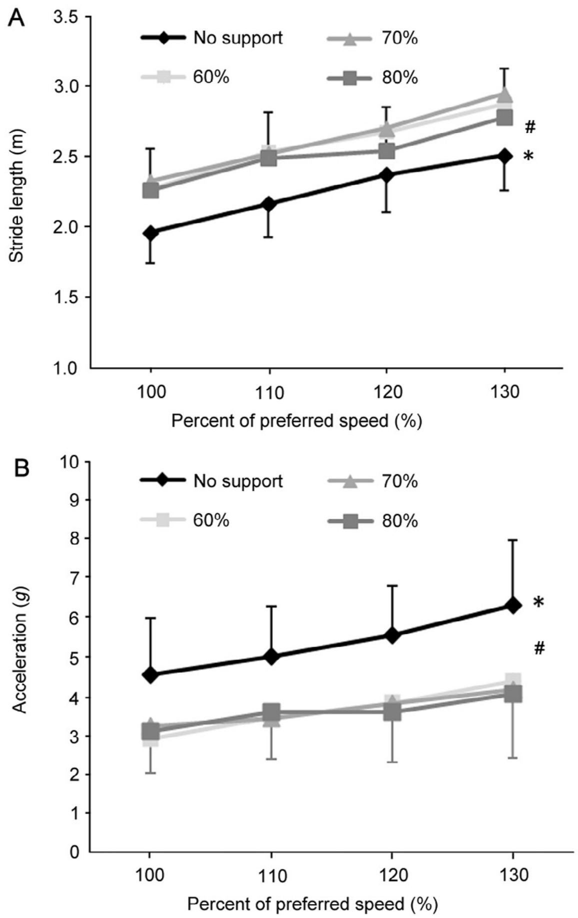

Fig. 1. Stride length (m) (A) and leg impact acceleration (g) (B) (mean ± SD) during running at different percentages of preferred speed (2.75 ± 0.36 m/s) at different levels of body weight support. *Significant main effect of body weight support ($p < 0.05$). # Significant main effect of velocity ($p < 0.05$).

levels ($p > 0.05$). Leg impact acceleration increased with velocity regardless of body weight support ($p < 0.05$).

4. Discussion

The main observations from this study were that SL and leg impact acceleration increased across running velocity (100%, 110%, 120%, and 130% of preferred velocity) regardless of body weight support. Another important observation was that both SL and leg impact acceleration were influenced by body weight support when compared to running with no body weight support. Specifically, when running with body weight support (60%, 70%, or 80% body weight support), SL was longer and impact accelerations less than when running with no body weight support (i.e., 100% body weight). However, neither SL nor impact acceleration were different across the different levels of 60%, 70%, and 80% body weight support (i.e., effective body weight being 20%–40% of body weight).

The SLs observed in this study are expected based upon previous work.[8,9,11] For example, Raffalt et al.[8] had subjects run at velocities of 2.8, 3.9, 5.0, 6.1 m/s and step length increased from 1.02 ± 0.04 m to 1.98 ± 0.10 m – which would equate to SLs of 2.04–3.96 m. In our study, SLs ranged from 1.98 m to 2.54 m across velocities of 2.73 m/s and 3.58 m/s. It is well established that SL increases across velocities[9,11,12] and therefore the SLs we observed for the velocity range used are reasonable.

The impact characteristics observed in this study were similar to previous work.[9,11,12,14] For example, while running at 100% of preferred velocity (2.73 ± 0.4 m/s) and 100% of body weight, leg impact accelerations were 4.53 ± 1.45 g in the present study. Mercer et al.[14] reported impact of 5.0 ± 1.6 g when running at 3.1 m/s (no body weight support). It is well established that impact acceleration increases with velocity.[9,11,12] Furthermore, our observation of decreased leg impact acceleration with increased body weight support are similar to previous research which has reported that when body weight support increased, ground reaction forces decreased.[1,3,5,8] However, it was interesting to observe that leg impact accelerations were not different among the body weight support levels that we used.

In the present study, it was observed that SL was about 15% longer when running with body weight support of 60%, 70%, or 80% compared to running with no body weight support. The change in SL may be an indication that muscles are used differently with body weight support. However, previous research has demonstrated that muscle activity patterns of lower extremity muscles are similar while running at a variety of body weight support conditions.[6,7] Furthermore, in general, muscle activity magnitude decreased with increases in body weight support,[4,6,7] except that the biceps femoris only tended to be different across high levels of support (i.e., 50%–80%).[7] Taken together, it seems that increased body weight support leads to decreased ground reaction forces[1,3,5,8] and (in general) muscle activity[4,6,7] whereas the overall pattern of muscle activity is the same across support conditions. Given this research,[1–8] we hypothesized that SL would decrease with increases in body weight support. However, SL did not change beyond running with 60% body weight support. In previous work using body weight support levels of 25%, 50%, and 75%[8] and 5%, 10%, and 15%,[2] SL increased as velocities increased. Furthermore, Cutuk et al.[1] reported that body weight support influenced SL differently for walking and running and illustrated an overall increase in SL for running with body weight support. Given our experiment was focused on high levels of body weight support only, it may be that there is a certain level of body weight support in which the changes in some parameters are subtle or do not occur. This is important with respect to equipment design in that there may not be much benefit to having an LBPP that provides support beyond 60% (for example). Nevertheless, combining the results of the present study with other published data,[1,2,8] it may be that there is a non-linear relationship between body weight support and SL when considering a broad range of body weight support. Furthermore, the lack of change in SL with an increase in body weight support from 60% to 80% may be related to the submaximal speeds used *vs.* a more demanding speed (e.g., maximal effort speed). Additional research is needed to better understand if the relationship between SL and body weight support is non-linear by testing smaller increments and a larger range of body weight support conditions. Our study is limited in that we focused only on high levels of body weight support.

There are other mechanisms to provide body weight support. For example, a person could run in shallow or deep water.[15–19] In these modes of exercise, an upward directed force is applied to the runner by the buoyancy force of water. Each mechanism of body weight support provides advantages and disadvantages that ultimately need to be understood by the user and/or practitioner. For example, deep water running provides resistance to any direction of movement via drag forces whereas running pattern during LBPP use is more similar to no body weight support.[18] The present study adds to this knowledge base in that it seems there are fewer gait changes made as body weight support is manipulated between 60% and 80% support (i.e., effective body weight of 20%–40%) as evident by the observations of no change in SL at these body weight support levels observed in the present study.

LBPP treadmill may be used as a mode of exercise in a rehabilitation program because of how much impact a patient can endure while running. From the present study, it was determined that impact was lower across velocities at each body weight support condition. Furthermore, impact increased at each body weight support level as velocity increased. Therefore, the clinician should be confident that a patient could use an LBPP treadmill in a way to modulate the amount of impact received simply by manipulating body weight support and velocity. That being said, it seems that impact at low velocities with low body weight support mimics impact at higher velocities with more body weight support. This means that a patient could run on an LBPP treadmill at high velocities with more body weight support and the impact will be similar to impact at lower velocities while running with no body weight support. This information is important for clinicians because it means that patients may be able to tolerate running rehabilitation at high velocities with body weight support and the impact would be similar to lower velocities with no body weight support. Nevertheless, clinicians need to consider carefully how best to use a body weight support treadmill for an injured athlete. Maybe there are advantages to selecting body weight support—speed combinations that mimic running with no body weight support while also minimizing the impact delivered to the lower extremity with each foot strike.

There are several limitations in this type of experiment. For example, this study was focused on running (*vs.* walking) and, furthermore, healthy subjects (*vs.* injured). It is not known how an injury would influence the self-selected speed or gait parameters like SL. Although including more body weight support and speed conditions would give a more complete picture about the relationship between SL, impact acceleration, speed, and body weight support, the present design included 16 conditions (4 speeds, 4 body weight support conditions). We gave subjects time to rest between conditions and limited the data collection time per condition (about 30–45 s) to minimize any influence of fatigue. In general, our subjects did not report any level of fatigue—but it would make sense to compare any fatigue effect on stride parameters and/or impact characteristics during body weight support *vs.* no body weight support. We also tested a specific order of conditions (i.e., no body weight support to highest body weight support, preferred speed to fastest speed). Although subjects adopt a running pattern very quickly, there is a need for research on whether or not gait parameters change with time.

5. Conclusion

In conclusion, it was determined that SL was increased and impact accelerations decreased with an increase in running velocity at each body weight support level (i.e., 60%, 70%, 80%). However, neither SL nor impact accelerations were different between each of the body weigh support conditions. If an LBPP treadmill is available, it may be a useful tool for clinicians to perform running exercises since impact magnitude can be modulated.

Acknowledgment

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