

## Research article

# COMPARATIVE KINEMATIC MEASURES OF TREADMILL RUNNING WITH OR WITHOUT BODY WEIGHT SUPPORT IN RUNNERS

Duane Millslagle ✉, Morris Levy and Nick Matak

Department of Health, Physical Education and Recreation, University of Minnesota Duluth, MN, USA

Received: 29 June 2005 / Accepted: 19 November 2005 / Published (online): 01 December 2005

### ABSTRACT

Treadmill walking and running using a supportive harness has been used as a training method to rehabilitate injured patients' walking or running gait. Comparison of full weight support (FWS) and body weight support (BWS) kinematic measures in competitive runners has received little attention. The purpose of this study was to compare selected FWS to BWS kinematic measures in healthy competitive runners. Ten male runners (age =  $21.4 \pm 1.5$  years) with a training regimen averaging 64 km per week at  $3.8 \text{ m}\cdot\text{s}^{-1}$  participated. All participants ran three 3-minute trials. The randomized trial conditions were: FWS, 20% BWS, and 40% BWS. All conditions were videotaped with 2 cameras and a 21-point, 3-D model was generated for analysis. From the position-time data, cycle length (CL), cycle frequency (CF), time of contact (TC), hip-, knee-, ankle- range of motion in degrees (H-ROM, K-ROM, and A-ROM, respectively), and vertical displacement of the center of mass (COM) were derived and compared. With increasing support conditions, cycle length increased. Cycle frequency, hip and ankle angle ranges, and COM vertical displacement decreased ( $p < 0.05$ ). However, the ankle angle range of motion varied little between 20% and 40 % BWS ( $p > 0.05$ ). BWS running produced significant changes in selected kinematic measures. These changes may provide insight into runners' behavior when using BWS in training or recovery from competition. Additional investigation of BWS training affect with competitive runners would be recommended.

**KEY WORDS:** Partial weight support, locomotion, gait characteristics, running.

### INTRODUCTION

Treadmill walking and running when combined with a supportive harness to provide body weight support (BWS) is being used in the retraining of the patient's walk and run gait. As walking and running gait improves, BWS is decreased and the patient is required to control greater percentages of body weight. The effectiveness of BWS in physical therapy research with disabled patients indicated significant improvement in their ability to walk independently, improve their balance, and increased their gait velocity, step frequency, and stride length

from the beginning of retraining to the end of training (Crompton et al., 2001; Field-Fote and Tepavac, 2002; Finch and Barbeau, 1985; Finch et al., 1991; Hesse et al., 1994; 1999; Lee and Farley, 1998; and Waagfjord et al., 1990).

Finch et al. (1991) studied normal male subject's walking gait under the influence of various BWS levels as compared to full weight support (FWS) gait using a treadmill. As the body weight was systematically removed and walking speed adjusted for BWS levels, the following changes in muscle activity, and mechanical changes in the walk were observed: 1) the amplitude in muscle activity

decreased during the weight bearing phase and increased during the swing phase of the walk; 2) the center of gravity was progressively raised, which resulted in decreased hip and knee angular displacement with a decrease in single-limb support. According to Finch et al. (1991), all these observed changes were not significantly different and indicated that BWS could be advantageous in walking gait retraining in normal subjects. Most angular differences of the hip and knee were attributed to harness support and the inability of the subjects to fully plant their foot on the treadmill.

McKay-Lyons et al. (2001) investigated BWS walking on cardio-respiratory changes in adults without impairment. Peak-expiratory gas exchange values changed little from a FWS to the BWS condition where 15% of the subject's mass was supported by a harness during treadmill exercise testing. The researchers contended that cardio-respiratory exercise testing protocols used in association with BWS could safely be used in testing patients with neurological injuries.

Body weight support systems have also been used in the study of locomotion in a microgravity environment. Reduced gravity research (Chang and Kram, 1999; Chang et al., 2000; 2001; Donelan and Kram, 2000; Farley and McMahon, 1992; He et al., 1991) have investigated the biomechanics, kinetic energy, and metabolic energy cost in walking or running on a reduced-gravity simulator and force treadmill by simply adding or reducing subject's body weight using a harness apparatus. This area of research required the use of some gravity-reducing apparatus such as the reduced-gravity simulator and force-measuring treadmill. In particular, force-measuring treadmills were specifically designed to measure vertical and horizontal ground reaction forces across different walking speeds and BWS conditions. Such studies have indicated the following changes in the walk and run gait from FWS to BWS condition: 1) the horizontal forces change more than vertical forces (Chang and Kram, 1999; Chang et al., 2001), 2) the exchange of kinetic energy as it related to the center of mass was effected by different walking and running velocity and with proportional, systematically reduced BWS conditions (Chang and Kram, 1999; Chang et al., 2001), 3) the vertical and horizontal ground reaction forces decrease (Chang and Kram, 1999; Chang et al., 2000; 2001; Kram et al., 1997), 4) the stride length and frequency increased (Farley and McMahon, 1992; Kram et al., 1997), 5) energy consumption as measured by the rate of oxygen consumption decreases (Farley and McMahon, 1992), and 6) the foot contact time during the supportive phase of the walk or run decreases (Chang et al., 2000).

There have been few reports describing the kinematic measures of BWS with experienced healthy runners. Our rationale was to examine FWS and BWS using a kinematics perspective with healthy athletes running on a treadmill at a high constant speed. We adopted a similar BWS strategy used in physical therapy and in the study of microgravity environment where the runner's mass was systematically reduced. We believed that the findings would provide meaningful interpretations about the similarities and differences between FWS and BWS treadmill running with experienced runners.

Several difficulties were discovered in reviewing the literature about BWS effects on running. There was a lack of consistency in the protocol used to reduce the subject's mass using a harness system. In addition, only He et al. (1991) examined BWS treadmill running using a speed greater than  $2.5 \text{ m}\cdot\text{s}^{-1}$ . Therefore, the purpose of this study was to compare FWS to BWS on kinematics characteristics of running throughout one running cycle at a high constant speed of  $3.8 \text{ m}\cdot\text{s}^{-1}$  or 7 mph. The kinematic changes from FWS to BWS in running on a treadmill that were of interest in this study are the angles of hip, knee, and ankle, foot contact time, vertical displacement of the center of mass, stride length and stride frequency. These kinematic measures are common in the analysis of the running gait and are related to research of basic running mechanics.

We used the FWS condition to determine if the kinematic measures in BWS running would change when their body mass was reduced 20% and 40%. It was hypothesized that BWS treadmill running produced significant changes in the kinematic measures compared to FWS treadmill running. Physical therapy and simulated microgravity research suggest that BWS running will cause a smaller vertical displacement of the center of mass, as compared to FWS running, associated with decreased contact time, decreased stride frequency, decreased hip, knee, and ankle angle ranges.

## METHODS

### *Subjects*

Ten male runners (age =  $21.4 \pm 1.5$  years, mass =  $68.4 \pm 3.3$  kg; means  $\pm$  S.D.) were recruited from the University of Minnesota Duluth cross-country team. The participants had previous treadmill running experience and maintained a training regiment averaging 64 kilometers per week at or faster than  $3.8 \text{ m}\cdot\text{s}^{-1}$ . A written informed consent was obtained from all subjects prior to participation in accordance

with the University Institutional Review Board policies. The subjects completed the Moderate Exercise Health Screening Report. This screening report was designed according to American College of Sports Medicine guidelines (2000) to screen for cardiovascular risk factors in subjects associated with submaximal exercise. Each subject's height, weight, resting blood pressure, and heart rate were measured. The presence of any significant risk factor associated with engaging in submaximal exercise would have prevented a potential subject from participation in the study.

### Equipment

A Woodway *Desmo S* TreadErgometer treadmill, a Pneumex lift system, and Z-lift suspension harness (Z-lift Corporation, Austin, TX) were used in this study. The subjects were fitted to a Z-lift harness (Figure 1) that was attached to the Pneumex lift system which lifted each subject by a percentage of body weight (Figure 2).



**Figure 1.** Z-Lift treadmill harness.

Two 60 Hz cameras (JVC TK1380) were positioned 90° apart, each synchronized to record the subject running on the treadmill (Figure 3). One camera was positioned approximately 45° in front of the frontal plane and the other camera was placed approximately 45° behind the frontal plane on the subject's left side. Subjects' running data were collected and analyzed using Peak Motus Version 7.0.1 motion analysis software (Peak Performance Technologies, Inc., Centennial, CO).

### Harness running training

Prior to data collection, the subjects participated in two separate harness running training sessions to become familiar with the body weight support (BWS) equipment and condition. Following a brief warm-up period including stretching and running on

the treadmill, each participant was fitted to the suspension harness. While the subject straddled the treadmill belt, the treadmill was set at 0% grade and a speed of 3.8 m·s<sup>-1</sup>. Each subject ran on the leveled treadmill for a period of 5 minutes at each of the FWS and BWS conditions. The FWS and BWS conditions during training were randomized for all the subjects.



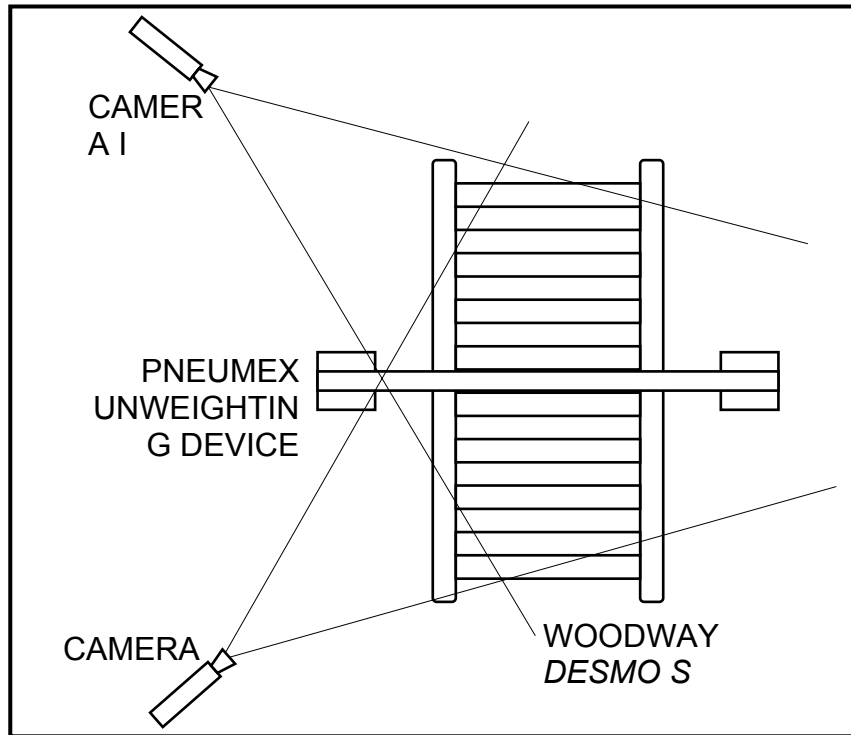
**Figure 2.** Pneumex Lift Pneumatic lifting system.

### Experimental procedures

The subject reported to the laboratory fully rested, was provided with a running top and bottom, and ran in their running training shoe. Each subject was fitted with the Z-lift harness and attached to the Pneumex lift system. Following a 5-minute treadmill running warm-up, the subject immediately performed three 3-minute running trials, one at each of the FWS and BWS conditions: 0 (FWS), 20% (20S), and 40% (40S) of body weight using the same treadmill grade and speed as in training. The FWS and BWS running conditions were randomized across the 10 subjects. The final 30 seconds of each trial were recorded with two 60 Hz cameras positioned at approximately 90 degrees about the frontal plane.

### Data processing and analysis

One running cycle was manually digitized for each FWS (0%) and BWS (20% or 40%) trials. A 21-point 3-D model was generated using Peak Motus® 7.0.1. The following landmarks were manually digitized for each trial: top of head, shoulders, elbow, wrists, 3<sup>rd</sup> metacarpals, hips, knees, lateral malleoli, heels, and toes. The position-time data were filtered using a fourth-order Butterworth filter at a cutoff frequency of 6 Hz. A residual analysis was used to determine the cutoff frequency.



**Figure 3.** Camera angle setup (overhead view). Two 60 Hz cameras are positioned approximately 90° apart.

From the position-time data, the following variables were derived: cycle length (CL), cycle frequency (CF), time of contact (TC), hip, knee, and ankle range of motion in degrees (H-ROM, K-ROM, and A-ROM, respectively). In addition, vertical displacement of the center of mass (CM) was calculated using anatomical segmental data published by de Leva (1996) as these data corresponded to our subject population. All variables were measured throughout one running cycle (defined as one full stride where the point the heel of the foot made contact to next time the heel of the same foot made contact). Time of contact was defined as the supported time by a single foot. Measurements that involved the left and right side were averaged for each subject before analysis. These measurements included time of contact, hip, knee, and ankle range of motion.

**Statistics**

Each variable was analyzed with a repeated

measures ANOVA ( $\alpha=0.05$ ) to ascertain differences between the supported- and full-weight-bearing conditions. Subsequent pairwise comparisons (Bonferroni) were used to further identify which running conditions significantly differ from each other.

**RESULTS**

Observation of mean values showed that all variables, except knee range of motion, either increased or decreased continuously when progressing from FWB to 40S (Table 1). As expected, since treadmill velocity was kept constant, cycle length increased while cycle frequency decreased with increasing support conditions. In addition, both hip and ankle angle ranges and COM vertical displacement decreased with increasing BWS. Statistical comparisons of the various weight support conditions revealed significant statistical differences for cycle length, cycle frequency, contact

**Table 1.** Means ( $\pm$  standard deviation) for variables.

Variables	FWB	20S	40S	F-value	p	Power
Cycle Length (m)	2.76 (.09)	2.88 (.10)	2.97 (.15)	32.86	<.0001	1.000
Cycle Frequency (Hz)	1.40 (.04)	1.34 (.05)	1.30 (.07)	36.11	<.0001	1.000
Contact Time (s)	.25 (.01)	.24 (.02)	.24 (.01)	4.57	.0248	.701
Hip Angle Range (deg)	58.7 (4.7)	53.1 (5.3)	49.3 (4.3)	19.62	<.0001	1.000
Knee Angle Range (deg)	106.5 (7.2)	108.3 (9.3)	107.2 (9.8)	.961	.4012	.185
Ankle Angle Range (deg)	48.6 (9.1)	45.8 (6.1)	44.5 (6.2)	4.215	.0315	.662
COM vertical displacement (m)	.12 (.01)	.10 (.01)	.09 (.01)	71.74	<.0001	1.000

**Table 2.** Pair wise comparisons (Bonferroni) p-values.

<b>Variables</b>	<b>FWB vs 20S</b>	<b>FWB vs 40S</b>	<b>20S vs 40S</b>
<b>Cycle Length</b>	.0003	<.0001	.0022
<b>Cycle Frequency</b>	.0001	<.0001	.0023
<b>Contact Time</b>	.033	.0108	.5991
<b>Hip Angle Range</b>	.0016	<.0001	.0219
<b>Knee Angle Range</b>	.1837	.5543	.4454
<b>Ankle Angle Range</b>	.0685	.0108	.3782
<b>COM vertical displacement</b>	<.0001	<.0001	<.0001

time, hip and ankle range of motion, and COM vertical displacement at a level of significance set at 0.05. The significant comparisons resulted in a high power rating (1.0) for cycle length, cycle frequency, hip and ankle range of motion and COM vertical displacement and moderate power rating for contact time (0.701) and ankle range (0.662). The non-significant knee angle comparison resulted in a low power rating (0.185). All pairwise comparisons for cycle length, cycle frequency, hip range of motion, and COM displacement were significant (Table 2). While contact time was found to be significant in the comparison test, it should be noted that the average values for FWS, 20S and 40S varied by 0.01 seconds. The ankle angle range of motion varied little between 20S and 40S, and did not yield a significant outcome.

## DISCUSSION

The study aimed to compare FWS to BWS on kinematic measures of treadmill running with experienced runners. It was hypothesized that BWS treadmill running would produce significant changes in kinematic measures compared to FWS treadmill running. Results indicated that, in the BWS conditions, contact time, associated with a smaller COM vertical displacement, decreased. In addition, stride frequency, hip, and ankle angle variables also decreased in comparison to FWS treadmill running. The knee angle from FWS to BWS conditions did increase but the change was not significant. Since speed was constant, the decreased stride frequency was linked to an increase in cycle length for the BWS conditions. These BWS results are similar to results found in physical therapy research involved in retraining a disabled patient's walk or run (Crompton et al, 2001; Finch et al, 1991; Lee and Farley, 1998) and microgravity research that compared kinematic measures of the walk or run from FWS to BWS (Chang et al, 2000; 2001; Donelan and Kram, 2000; Farley and McMahon, 1992; Kram et al., 1997).

The results of this study indicate that runners may have adjusted their leg action from FWS across the BWS conditions in a linear fashion, that is, as

more weight is being supported, the hip, knee, and ankle angle resulted in less leg compression and a straighter leg through out the running cycle. It has been described that high stiffness of the leg is achieved by attaining a joint as straight as possible when the foot is in contact with the ground (Blickman, 1989). In this study, as more weight is being supported, the runner's leg stiffness increased because the angular changes in the hip and ankle decreased while the knee increased which in combination produced a leg that was straighter during the running cycle.

A closer examination of vertical displacement as it relates to leg angles, cycle length, and stride frequency throughout one full running cycle from FWS across the BWS conditions was also conducted. The runners' vertical displacement was the greatest in the FWS and decreased as more weight was being supported across the BWS conditions. In BWS conditions, the harness forces on the runners prevented their center of mass to drop as compared to the FWS conditions. The runners adjusted their running to a higher center of mass in the BWS conditions by less hip and ankle angular displacement while the angular displacement of the knee increased. These findings were consistent with microgravity research that reported similar findings involving walkers (Chang and Kram, 1999; Chang et al., 2001), where with less vertical displacement, the hip and ankle during the swing phase and greater cycle length in the stride enabled the knee to have a greater extension on foot contact. Effects of supporting more weight in producing a shorter foot contact time were consistent with studies (Lee and Farley, 1998) that used a spring mass model to study running, which predicted that as leg stiffness increased foot contact time with the ground would decrease.

Practical issues in using a harness support system and treadmill may provide insight into how runners might respond to BWS during athletic training. When systematically displacing the injured weight, the injured runner experiences a lower angular leg displacement throughout the running cycling which leads to a lower stretch of the leg muscles. The runner's stride frequency increases

while the contact with the ground is less. This enables the runner to increase the amount of running practice with less leg angular change and foot contact force. The healthy runner may be able to use BWS running to recover from intense training and competitions due to the lower musculoskeletal stress from less vertical displacement of weight, a lower stretch of the leg muscles, and decreased foot contact while running. The practical significance of contact time change may be limited for short running bouts, but should not be overlooked during longer training sessions. For instance, the compounded contact time on a single foot for a one-hour run at 20S would be decreased by approximately 50 seconds. The assumed merits of body weight suspended running in training and recovery from competition merits further investigation.

## CONCLUSIONS

This study compared FWS and BWS on kinematics characteristics with healthy runners. The kinematic measures of angles of hip, knee, and ankle, foot contact time, vertical displacement of the center of mass, stride length and stride frequency were used to analyze each runner's gait. BWS running produced significant changes in selected kinematic measures. These changes may provide insight into runners' behavior when using BWS in training or recovery from competition. Additional investigation of BWS training affect with competitive runners would be recommended.

## REFERENCES

- American College of Sports Medicine. (2000) *Guidelines for exercise testing and prescription*. 6<sup>th</sup> edition. Philadelphia, PA: Lippincott, Williams, & Wilkins.
- Blickman, R. (1989) The spring-mass model for running and hopping. *Journal of Biomechanics* **22**, 1217-1227.
- Chang, Y., Hamerski, C.M. and Kram, R. (2001) Applied horizontal force increase impact in reduced-gravity running. *Journal of Biomechanics* **34**, 679-685.
- Chang, J., Hsuan-Wen, C.H., Hamerski, C.M. and Kram, R. (2000) The independent effects of gravity and inertia on running mechanics. *Journal of Experimental Biology* **203**, 229-238.
- Chang, Y. and Kram, R. (1999) Metabolic cost of generating horizontal forces during human running. *Journal of Applied Physiology* **86**, 1657-1662.
- Crompton S., Khemlani, M., Batty, J., Ada, L., Dean, C. and Katrak, P. (2001) Practical issues in retraining walk in severely disabled patients using treadmill and harness support systems. *Australian Journal of Physiotherapy* **47**, 211-213.
- Donelan, J.M. and Kram, D. (2000) Exploring dynamic similarity in human running using simulated reduced gravity. *Journal of Experimental Biology* **203**, 2405-2415.
- de Leva, P. (1996) Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics* **29**, 1223-1230.
- Farley, C.T. and McMahon, T.A. (1992) Energetics of walking and running: insights from simulated reduced-gravity experiments. *Journal of Applied Physiology* **73**, 2709-2712.
- Field-Fote, E.C. and Tepavac, D. (2002) Improved intralimb coordination in people with incomplete spinal cord injury following training with body weight support and electrical stimulation. *Physical Therapy* **82**, 707-715.
- Finch, L. and Barbeau, H. (1985) Influences of partial weight bearing on normal human gait: the development of a gait retraining strategy. *Canadian Journal of Neurological Science* **12**, 183.
- Finch, L., Barbeau, H. and Arsenault, B. (1991) Influence of body weight support on normal human gait: development of a gait retraining strategy. *Physical Therapy* **71**, 842-856.
- He, J., Kram, R., and McMahon, T.A. (1991) Mechanics of running under simulated low gravity. *Journal of Applied Physiology* **71**, 863-870.
- Hesse, S., Bertelt, C. and Schaffrin, A. (1994) Restoration of gait in nonambulatory hemiparetic patients by treadmill training with partial weight support. *Archives of Physical Medicine and Rehabilitation* **75**, 1087-1093.
- Hesse, S., Konrad, M. and Uhlenbroch, D. (1999) Treadmill walking with partial body weight support versus floor walking in hemiparetic subjects. *Archives of Physical Medicine and Rehabilitation* **80**, 421-427.
- Kram, R., Domingo, A. and Ferris, D.P. (1997) Effect of reduced gravity on the preferred walk-run transition speed. *Journal of Experimental Biology* **200**, 821-826.
- Lee, C.R. and Farley, C.T. (1998) Determinates of the center of mass trajectory in human walking and running. *Journal of Experimental Biology* **201**, 2935-2944.
- McKay-Lyons, M., Makrides, L. and Speth, S. (2001) Effect of 15% body weight support on exercise capacity in adults without impairments. *Physical Therapy* **81**, 1790-1800.
- Waagfjord, J., Levangle, P.K. and Certo, C.M.E. (1990) Effects of treadmill running on gait in hemiparetic patient. *Physical Therapy* **70**, 549-558.

**AUTHORS BIOGRAPHY**

---

**Duane MILLSLAGLE****Employment**

Associate Professor of Motor Behavior at the University of Minnesota Duluth.

**Degree**

PhD

**Research interests**

Learning and relearning of motor and sport skills associated with teaching, exercise science, and physical therapy.

**E-mail:** dmillsla@d.umn.edu

---

**Morris LEVY****Employment**

Assistant Professor of Biomechanics at the University of Minnesota Duluth.

**Degree**

PhD

**Research interests**

Sports Biomechanics; performance improvement, injury prevention and rehabilitation.

**E-mail:** mlevy@d.umn.edu

---

**Nick MATAACK****Employment**

Graduate Student, Physical Therapy, College of St-Scholastica, Duluth, MN.

**Degree**

BAS

**Research interests**

Running, injury prevention, and rehabilitation.

---

**KEY POINTS**

- Running kinematics change gradually with increasing levels of body weight support.
- At constant speed, center of mass vertical displacement, lower leg angular displacement, foot contact time and cycle frequency decrease significantly from FWS to 40S.
- Harness running can have beneficial effects in healthy runners recovering from intense bouts of exercise.

✉ **Dr. Duane Millslagle**

Associate Professor, Health, Physical Education & Recreation Department, SpHC 115, University of Minnesota Duluth, Duluth, MN 55811, USA