Technical Report

Plantar Pressure Reduction in an Incremental Weight-Bearing System

Background and Purpose. Harness-supported treadmill ambulation has been advocated for patients to provide reduction in weight bearing to healing tissues and to reduce the energy cost of treadmill ambulation. The purposes of this technical report are to analyze the ability of one of these devices (Zuni Exercise System) to support a specific percentage of a subject's body weight during walking and running and to explore the relationship of unloading to pressure reduction in selected plantar surface regions of the foot. **Subjects.** Ten male volunteers with no known foot pathology participated. **Methods.** In-shoe plantar pressure and vertical ground reaction forces (GRFs) were measured during walking and running at full body weight and at 20% of body weight supported. **Results.** Walking at a setting of 20% of body weight supported resulted in a reduction of the first and second vertical force peaks of 23.8% (SD=7.3%) and 27.2% (SD=4.1%), respectively. The total force-time integral during walking unloaded was 22.8% (SD=3.3%). During running, the active vertical force peak and total force-time integral were reduced by 19.9% (SD=6.0%) and 20.0% (SD=3.3%), respectively, in the unloaded condition. Plantar pressures were reduced from 6.8% to 27.8% in the body weight-supported conditions. The reduction was variable across different regions of the foot. **Conclusion and Discussion.** The Zuni Exercise System appears to reduce the vertical component of the GRF during walking and running with 20% of body weight supported. Plantar pressures were reduced during body weight-supported conditions, but the reduction varied at different regions of the foot. [Flynn TW, Canavan PK, Cavanagh PR, Chiang J-H. Plantar pressure reduction in an incremental weight-bearing system. *Phys Ther.* 1997;77:410–416.]

Key Words: *Gait, Ground reaction force, Harness-supported treadmill ambulation, Plantar pressure.*

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People with injuries often experience lower-extremity pain and weakness during weight-bearing activities, which often leads rehabilitation specialists to avoid weight-bearing activities when designing therapeutic exercise programs for their patients. Instead, open kinetic chain (ie, non-weight-bearing) activities are often substituted during the rehabilitation program. There is little evidence, however, that open kinetic chain training results in improved performance of closed kinetic chain (ie, weight-bearing) functional tasks.[1–3] With increasing frequency, the rehabilitation literature and continuing education courses have been promoting the use of functional weight-bearing activities during rehabilitation programs to more closely replicate the activity of daily living or sports activity in which an individual may typically be involved.

Use of various devices, such as crutches and walkers, and pool therapy reduce the amount of loading on an injured limb. The drawbacks of these methods are that precise measurements of load reduction are not possible and that patients' movements can be encumbered while the speed of movement is reduced. Additionally, some patients are unable to use assistive devices due to weakness or injuries of the upper extremities. Recently, equipment has become available that provides harness-supported treadmill ambulation. *Harness-supported treadmill ambulation* refers to decreasing an individual's effective body weight by a given amount using a supporting harness and counterbalance system that accommodates the rise and fall of the body during treadmill ambulation.[4] The reduced weight-bearing machines use a variety of methods to achieve weight reduction, including the use of counterbalance weights, pneumatics, and the use of springs. Harness-supported treadmill ambulation has been advocated for patients as a means of minimizing load to healing tissues and conserving energy during exercise.[5] Finch et al[6] proposed that supporting a percentage of body weight during gait retraining may facilitate the expression of a more normal gait pattern. This modality has been used in the management of stress fractures and tendon repair,[7] osteoarthritis,[8] and lumbar intervertebral disc pathology[9]; in gait rehabilitation of patients with strokes[10]; and in retraining of persons with amputations.[5] In particular, the use of harness-supported treadmill ambulation in retraining of persons with amputations has been advocated on the grounds that it can reduce pain and skin breakdown during the initial phases of prosthetic use.[5]

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The study protocol was approved by the Human Use Committee at The Pennsylvania State University.

The opinions or assertions contained herein are those of the authors and are not to be construed as official or as reflecting the views of the Department of the Army, the Department of Defense, or the US Government.

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Table 1.
Difference in Vertical Component of the Ground Reaction Force (Expressed as a Percentage) During Walking and Running With Full Body Weight and With Body Weight Supported[a]

	Peak 1 Reduction			Peak 2 Reduction			Total Force Reduction		
	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range
Walking	23.8*	7.3	12.2–33.2	27.2*	4.1	22.1–34.5	22.8*	3.3	18.4–28.7
Running	19.9*	6.0	13.5–27.9				20.0*	3.3	13.7–25.0

[a] Asterisk (*) indicates significant difference ($P<.05$).

Hesse et al[10] reported gait restoration of nonambulatory patients with chronic hemiparesis using an intervention protocol that included treadmill training with partial body weight supported. One device used in such protocols, the Zuni Exercise System,* mechanically offsets the patient's body weight in 1-lb increments, yet accommodates for the vertical oscillations experienced during walking and running. This device has been shown to reduce the oxygen cost of treadmill ambulation in persons without impairments and patients with osteoarthritis and amputations.[4,5,8]

Finch et al[6] evaluated a harness-supported treadmill ambulation system and reported that when 30%, 50%, and 70% of body weight were supported during walking, there was a reduced mean amplitude in muscles required for weight acceptance (erector spinae and gluteus medius muscles) and push-off (medial gastrocnemius muscle). Additionally, there was an increase in mean amplitude in the tibialis anterior muscle during the swing phase of gait. Finch et al reported that the mechanical constraints of the support system resulted in gait alterations, including a raised center of gravity with a limited downward excursion of the center of gravity throughout the gait cycle.

If a harness-supported treadmill device is to be used in rehabilitation to limit weight bearing, a determination should be made as to whether the device actually reduces the vertical ground reaction force (GRF) experienced by the patient. To our knowledge, there have been no studies that have examined whether these devices reduce GRFs. The purposes of our study were to analyze whether the Zuni Exercise System maintains a prescribed percentage of a subject's body weight reduction during walking and running and to explore the relationship of unloading to pressure reduction in selected plantar surface regions of the foot. The specific aims of the study were (1) to determine whether the Zuni Exercise System actually reduces vertical GRFs by 20% at the experimenter-chosen level of 20% of body weight reduction and (2) to determine whether the Zuni Exercise System reduces pressure by 20% under five selected foot regions during an experimenter-chosen level of 20% of body weight reduction.

Method

Subjects

Ten men with no known foot abnormality or pathology participated in the study. The subjects had a mean age of 30 years (SD=3, range=24–34), a mean weight of 75.4 kg (SD=8.3, range=68–91), and a mean height of 174.4 cm (SD=6.4, range=165–185). Prior to testing, the subjects were briefed and each subject signed an informed consent form.

Instrumentation and Testing Procedures

Vertical GRF and plantar pressures were measured using the PEDAR in-shoe pressure measuring system.† The PEDAR system uses flexible insoles that can be placed directly between a person's foot and shoe. The PEDAR system uses capacitance-based pressure-sensing insoles, which consist of a matrix of 99 sensors covered with a thin layer of polyvinyl chloride (approximately 2.5 mm in thickness). The PEDAR system provides either on-line measurement or a maximum stored measurement of 1,000 frames at a sampling frequency of 50 Hz. The insoles were calibrated according to the manufacturer's specifications prior to testing. The PEDAR insoles have been shown to provide fairly low variability with repeated loadings and to produce a linear response to increased loading levels.[11] The accuracy of PEDAR-collected force measurements has shown reasonable conformity with Kistler force platform measurements[12] in walking, although there is a tendency for the second vertical peak to be underestimated. The frequency response of the PEDAR system also does not allow accurate recording of the initial impact peak of the vertical GRF during running. All the subjects wore their own running shoes. Following placement of the insoles in the running shoes, each subject randomly performed the following four treadmill activities: walking at 3.5 mph with full body weight (W), walking at 3.5 mph with 20% of body weight supported (WS), running at 6.0 mph with full body weight (R), and running at 6.0 mph with 20% of body

* SOMA Inc, 10711 Burnet Rd, Austin, TX 78758.

† Novel USA, 964 Grand Ave, St Paul, MN 55105.

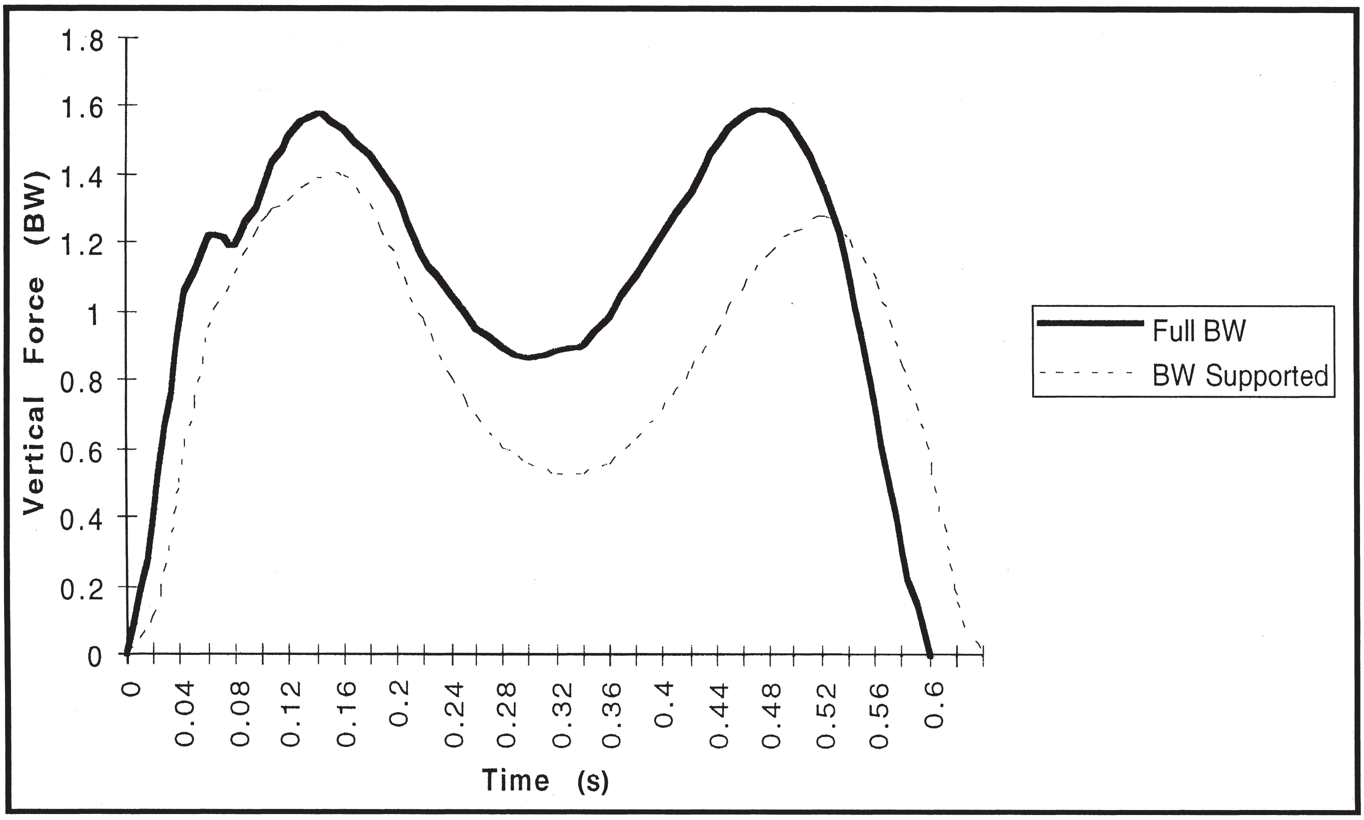

Figure 1.
A representative sample of the vertical force-time curves for walking in the loaded and unloaded conditions. BW=body weight.

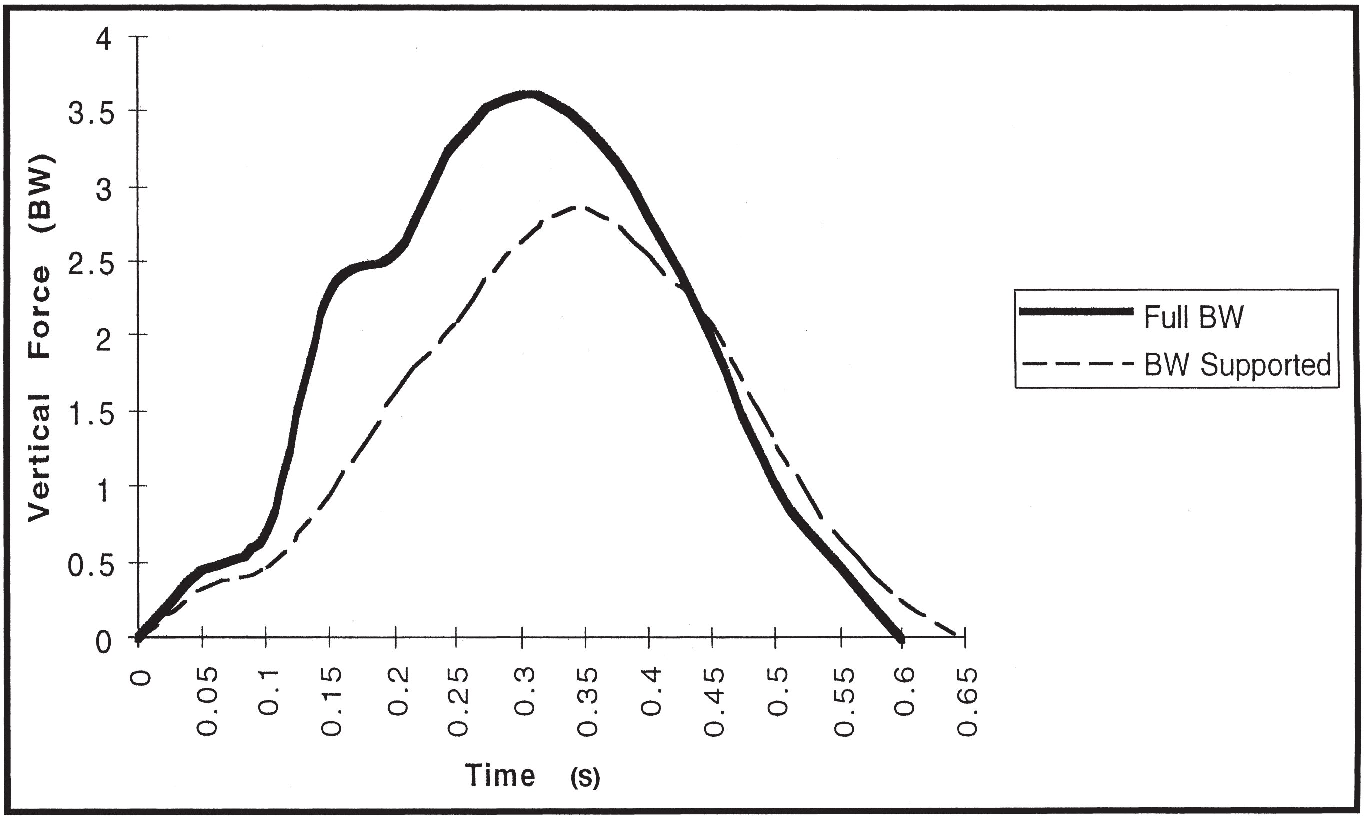

Figure 2.
A representative sample of the vertical force-time curves for running in the loaded and unloaded conditions. BW=body weight.

Table 2.
Percentage of Reduction of Regional Peak Pressure During Walking and Running With 20% of Body Weight Supported[a]

	Heel			Midfoot			Lateral Forefoot			Medial Forefoot			Toes		
	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range
Walking	16.6*	11.0	10–43	24.1*	13.9	0–50	24.1*	13.9	3–44	22.2*	18.3	6–42	8.0	24.4	0–47
Running	27.8*	18.0	4–65	22.2*	10.2	2–35	12.9*	9.8	0–23	6.8*	10.0	0–22	15.8*	16.3	0–41

[a] Asterisk (*) indicates significant difference ($P<.05$).

weight supported (RS). A minimum of 10 right and left footstrikes were collected, from which 3 footstrikes were chosen at random for the analysis.

Data Analysis

The vertical component of the GRF was determined from the PEDAR data files via the manufacturer's conversion program. These files were then used to determine peak vertical forces and the force-time integral for each of the analyzed steps. A regional peak pressure analysis was used, which divided the foot into five regions: toes, lateral metatarsal, first metatarsal, midfoot, and heel. The regional peak pressures were calculated by choosing the maximum pressure value of each frame within each of the five foot regions using an author-developed Quick-Basic program.‡

Statistical evaluation of the data was performed using a one-way analysis of variance. When a significant F ratio was found between the full body weight and body weight-supported conditions, a *post hoc* paired *t* test was performed on each variable. Significance was set at $P<.05$.

Results

Vertical Force

The differences in the vertical component of the GRF during walking and running with full body weight and with body weight supported, expressed as percentages of reduction, are presented in Table 1. Walking and running with body weight supported resulted in a difference from walking and running with full body weight for each of the three force variables measured. Representative samples of the vertical force-time curves for walking and running in the loaded and unloaded conditions are presented in Figures 1 and 2.

Plantar Pressures

The differences in regional peak pressure during walking and running with full body weight and with 20% of body weight supported, expressed as within-subject percentages of reduction, are presented in Table 2. A mean range of pressure reduction of 6.8% to 27.8% was found over all conditions and regions. For all regions except the toe region during walking, a reduction of peak plantar pressure occurred during the unloaded conditions. The absolute values of peak plantar pressure for the different regions are presented in Table 3. In each subject, during all four conditions, the peak pressure occurred in the medial forefoot region (first and second metatarsal heads). Figures 3 and 4 display the foot regional mean pressures and standard deviations relative to the mean peak pressure of the medial forefoot region in the walking and running conditions, respectively.

Discussion

The results of our study support the notion that at an experimenter-chosen level of reduction, the Zuni Exercise System reduced the vertical forces acting on the lower limb in a consistent and predictive manner during both walking and running. The oscillatory nature of the gait cycle presents an unloading device with the challenge of accommodating for this changing pattern without disrupting the natural gait rhythm. The design of the Zuni Exercise System incorporates a linear actuator attached to a spring as a method for accommodating normally encountered gait oscillations (G Hickinbotham, Production Director, Soma Corporation, Austin, Tex; personnal communication; 1996). The operator adjusts the Zuni Exercise System by selecting a level of body weight supported, and the system, through the linear actuator, makes the appropriate modifications in the spring tension.

Nigg[13] defined the *vertical impact force peak* in human locomotion as the force that results from the collision of the foot at first ground contact that reaches a maximum level earlier than 50 milliseconds. Nigg described the *active vertical force peak* as the forces generated by movement that is entirely controlled by muscular activity. During walking, the vertical impact force peak was present in the W condition but absent in the WS condition. The absolute magnitude and shape of the vertical impact peak should be viewed with caution, given the data-collection frequency of 50 Hz and the frequency response of the PEDAR insole mentioned earlier. In both walking conditions, two force peaks were present, the first being associated with the deceleration phase and the second being associated with the acceler-

‡ Microsoft Corp, 16011 NW 36th Way, Redmond, WA 98073.

Table 3.
Regional Peak Pressure (in Kilopascals) During the Four Treadmill Conditions at the Five Selected Regions of the Foot

	Walking			Walking Supported			Running			Running Supported		
	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range
Heel	239	81	143–376	197	66	120–323	265	150	95–550	200	70	80–283
Midfoot	89	28	33–130	76	30	30–126	134	49	70–210	108	32	60–156
Lateral forefoot	193	97	126–450	147	77	80–343	273	139	130–600	237	135	120–526
Medial forefoot	261	119	150–476	196	80	103–350	386	250	180–996	378	227	183–863
Toes	247	148	90–550	210	108	93–396	230	134	130–456	210	73	113–303

ation phase. In general, walking with a setting of 20% of body weight supported resulted in reductions of the first and second vertical force peaks of 23.8% (SD=7.3%) and 27.2% (SD=4.1%), respectively. These reductions were somewhat greater than the selected Zuni Exercise System setting. The total force-time integral during walking in the unloaded condition was 22.8% (SD=3.3%), which was slightly greater than the selected 20% reduction. During running in the body weight-supported condition, the active vertical force peak and the total force-time integral were reduced by 19.9% (SD=6.0%) and 20.0% (SD=3.3%), respectively.

The vertical GRF curves during the W and WS conditions displayed the stereotypical bimodal pattern (Fig. 1). Throughout foot contact, the vertical GRF curve showed a decrease in magnitude in the WS condition when compared with the W condition. The vertical GRF curves during the R and RS conditions did not display the vertical impact force peak (Fig. 2) that typically occurs about 5 to 30 milliseconds after first ground contact.[13] The lack of the vertical impact force peak is likely to be a consequence of the relatively slow sampling frequency of 50 Hz and the frequency response of the PEDAR insoles. Additionally, the slope of the first half of the vertical GRF was steeper in the R condition than in the RS condition. In general, the vertical GRF curve showed a decrease in magnitude in the RS condition when compared with the R condition, but this decrease did not appear to be as consistent as that seen in the walking conditions.

Additionally, this study explored the relationship of force unloading to pressure reduction in selected plantar surface regions of the foot. Generally, a 20% of body weight-supported condition resulted in reductions in plantar pressure under all regions of the foot except the toe region during walking, where a nonsignificant reduction occurred. The variability of the reduction across subjects, however, was substantial (6.8%–27.8%), implying that a given regional pressure may not be as predictably reduced in a body weight-supported condition. This observation is important because ambulatory assistive devices are often used in the treatment of plantar ulcers in an effort to provide pressure relief. A reduction in force in a controlled manner would logically lead to pressure reduction in a predictable manner. Our results, however, show that the pressure reduction is not consistently equal over all regions of the foot. In particular, the forefoot, which is a common site of ulceration, appears to undergo the least reduction in plantar pressure during running. This finding highlights the difficulty a practitioner has in confidently reducing pressure by a set amount in a selected foot region by using assistive devices without direct in-shoe measurements. In this study, however, we tested only subjects with no known

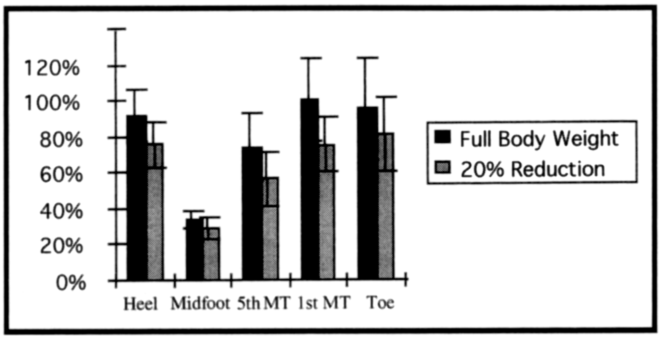

Figure 3.
Means and standard deviations for plantar pressure during walking, viewed as a percentage of the maximum region (first and second metatarsal heads). MT=metatarsal.

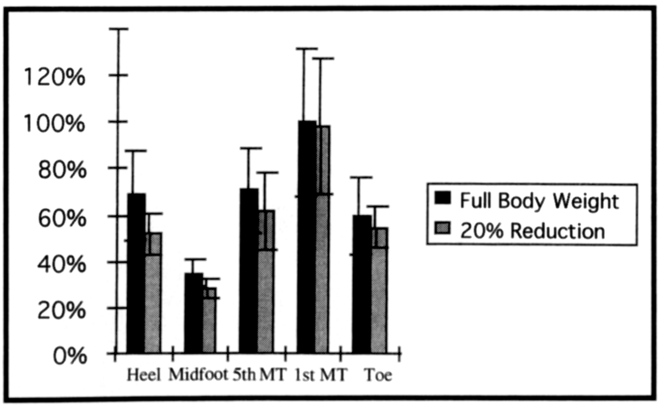

Figure 4.
Means and standard deviations for plantar pressure during running, viewed as a percentage of the maximum region (first and second metatarsal heads). MT=metatarsal.

foot pathology. Additional research involving subjects with plantar ulceration is needed to address this speculation.

Conclusion

The Zuni Exercise System appears to be a valid instrument for predictably reducing the vertical component of the GRF during walking and running at the 20% of body weight setting. In general, plantar pressures were reduced during body weight-supported conditions, but the reduction was variable across different regions of the foot. Future analysis of this system should include both a wide range of gait speeds and a wide range of conditions for percentage of body weight supported.

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