Cardiovascular Responses During Nonweight-Bearing and Touchdown Ambulation

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The purpose of this study was to compare selected physiological responses of nonweight-bearing (NWB) and touchdown (TD) ambulation using axillary crutches. Ten subjects walked at a constant rate for five minutes at a mean velocity of 48.42 m/min for NWB and 48.95 m/min for TD. Weight bearing was controlled with an augmented sensory feedback device. Heart rate, blood pressure, oxygen consumption, and perceived exertion were measured. Myocardial oxygen consumption was estimated from heart rate alone and from the double product of systolic blood pressure and heart rate. Oxygen consumption and systolic blood pressure were similar for NWB and TD. Heart rate and myocardial oxygen consumption were significantly higher during NWB, and this was attributed to greater upper and lower extremity isometric exercise required for NWB versus TD ambulation. Physiologically, TD may be preferable to NWB for persons who are deconditioned or limited in their exercise capacity.

Key Words: *Blood pressure, Crutches, Exertion, Heart rate, Oxygen consumption.*

The use of restricted weight bearing is widespread in adult rehabilitation. Clinically, the need for restricted weight bearing is often indicated for lower extremity fractures, joint replacements, rheumatoid conditions, immediate postoperative fittings, and lower extremity vascular disorders.[1] Historically, the treatment of choice has been nonweight-bearing (NWB) bed to chair transfer or NWB ambulation. Clinical experience has shown that balance problems, decreased cardiovascular endurance, and inadequate upper extremity strength may hinder a NWB program. Partial weight-bearing (PWB) ambulation has received little attention in the literature until quite recently.[1] Rydell implanted a strain gauge into the hip of one subject and determined that NWB was mechanically more stresssful to the hip than PWB.[2] Physiologically, the cardiovascular response of NWB versus PWB is also an important consideration. The patient with an orthopedic problem compounded by a cardiovascular disease faces unique problems in the rehabilitation process. Cardiovascular response to restricted weight bearing is a factor that can affect patients' abilities to return to their premorbid life style.

Few studies have been conducted on the energy expenditure of PWB ambulation. Cordrey et al measured oxygen consumption ($\dot{V}O_2$) during ambulation in patients who suffered a fracture of the hip.[3] The subjects performed NWB or PWB with crutches, walkers, or parallel bars. They reported no significant differences in the $\dot{V}O_2$ of the subjects as they used the assistive devices. The absence of a control group and unmeasured and uncontrolled velocity of ambulation limited the interpretation of their data.[3] McBeath et al studied 10 healthy subjects during NWB, PWB, two-point alternating, and swing-through gaits.[4] Each subject used a cane, axillary crutches, and Lofstrand crutches. The investigators found a significant decrease in velocity, and a 33 to 78 percent increase in $\dot{V}O_2$ between assisted and unassisted ambulation. Statistical comparisons between the different weight-bearing gaits for the same assistive device were not addressed.

Myocardial function during assisted ambulation was not assessed by either Cordrey et al[3] or McBeath et al.[4] Measurement of myocardial oxygen consumption ($M\dot{V}O_2$) may be determined by direct invasive means or through noninvasive predictors of $M\dot{V}O_2$. The use of indirect indices of $M\dot{V}O_2$ has been demonstrated to be valid.[5] Those indices that are easily measured include heart rate (HR) alone and the double product of HR and systolic blood pressure (RPP). The correlation between $M\dot{V}O_2$ and HR alone, between $M\dot{V}O_2$ and RPP, and between $M\dot{V}O_2$ and $\dot{V}O_2$ have been shown to be r = .88, .90, and .80, respectively.[5] Because $\dot{V}O_2$ has not been shown to be a relatively high predictor of $M\dot{V}O_2$, earlier PWB studies have investigated the amount of external or total body work rather than the degree of myocardial work.

Ratings of perceived exertion is a psychophysical scale that has also been used to measure the intensity of physical work. Borg developed this scale to measure the perceptual response to an exercise stimulus.[6] He and other investigators have found a correlation of .80 to .90 between HR and perceived exertion.[6] This scale has been shown to be a valid, reliable and simple means of determining a person's response to exertion.

The amount of weight placed on the PWB extremity during ambulation is another factor that has not been controlled in these studies.[3,4] Cordrey et al did not offer any operational definition of PWB.[3] In the study by McBeath et al, all subjects

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TABLE 1
Summary of Experiment Procedure and Data Collection

Procedure Order	Procedure	Time (min)	$\dot{V}O_2$	HR	SBP	Borg Scale	Velocity	Step Length	Step Rate
1	Practice session	Variable	...	X	...	...	...	...	...
2	Minipilot (NWB or TD)[a]	1	...	X	...	...	X	X	X
3	Minipilot (NWB or TD)[a]	1	...	X	...	...	X	X	X
4	Rest	5	X	X	X	...	...	...	...
5	Trial (NWB or TD)[a]	5	X	X	X	X	X	X	X
6	Rest	5	...	X	X	...	...	...	...
7	Trial (NWB or TD)[a]	5	X	X	X	X	X	X	X

[a] NWB and TD were performed in an alternating order for each subject.

practiced placing 9.1 kg (20 lb) of weight on a scale before they performed the test.[4] The same amount of weight was used for PWB regardless of the subject's body weight. Warren and Lehmann studied the effectiveness of common tools for PWB and found that using a scale offered limited effectiveness in controlling weight bearing.[7] The improvement of augmented feedback devices now permits clinicians and researchers to control more accurately weight placed on an extremity during PWB.[8]

The purpose of this study was to compare the cardiovascular responses of NWB and touchdown (TD) ambulation using axillary crutches. Weight bearing was defined in terms of percentage of body weight and scientifically controlled with the use of a Limb Load Monitor (LLM).* Velocity was controlled during the two modes of ambulation to permit accurate comparisons.

METHOD

Subjects

The subjects consisted of 10 healthy adults, six men and four women. The mean group age was 26.7 ± 3.91 years, mean group height was 1.68 ± .11 m (5.5 ± 4 ft), and mean weight was 62.97 ± 15.44 kg (138.8 ± 34 lb). All subjects reported no history of cardiovascular or neurological disorders, diabetes, rheumatoid arthritis, active pulmonary disease, or orthopedic disorder within the past five years. Subjects were instructed not to eat or drink for the two hours before the laboratory session. Food restrictions were imposed to obtain more accurate $\dot{V}O_2$ values. Subjects participated in one laboratory session consisting of one NWB and one TD ambulation trial. All subjects signed an informed consent form. This research project was approved by the Sargent College Clinical Research Review Committee.

Instrumentation

Oxygen consumption was determined from expired air using the Wilmore-Costill semiautomated system.[9] Subjects wore a headpiece with a connected mouthpiece and an attached two-way valve. The valve allowed unrestricted inspiration of air. Expired air was channeled through tubing (25.4 mm [1 in] inner diameter) and was collected in Douglas bags.† Subjects wore nose clips to prevent the escape of expired air through the nasal passage. Douglas bags were held by an assistant, and air was collected without interrupting the subject's activity. Expired air was analyzed using a Beckman E2 Oxygen Analyzer‡ and Beckman LB2 Carbon Dioxide Analyzer.‡ We used gases of known quantity to calibrate the analyzers. We measured the volume of expired air with a Chain Compensated Gasometer† and corrected the reading to standard temperature and pressure.

To determine the HR, we placed surface electrodes distal to the sternal notch, at the left V_5 position, and a ground was placed at the right V_5 position. The telemetry receiver** was attached to a Hewlett-Packard HP-1500BF oscilloscope and electrocardiograph.** Systolic blood pressure (SBP) was measured noninvasively with a sphygmomanometer. Subjective analysis of the work performed was analyzed by using the Borg scale of perceived exertion.[6]

The LLM* was used to ensure proper weight bearing. The transducer, in the form of a foot plate, was inserted into the shoe and attached to a control box that was tied to each subject's belt. The pitch of the auditory feedback indicated improper weight bearing.

Procedure

We defined NWB ambulation as ambulation with the foot of the designated extremity off the ground throughout the gait sequence. During TD ambulation, the foot of the designated extremity progressed heel to toe. Weight bearing was restricted to 10 percent of the body weight for the TD extremity to allow close, clinical comparison with NWB. Auditory feedback of the LLM determined maintenance of NWB and TD. A two-point gait sequence was used for both modes of ambulation. The subject walked along a premarked circular path measuring 12.43 m (40.8 ft) in circumference.

Table 1 is a summary of the procedure that all subjects followed. First, the subjects practiced crutch walking until they were proficient at the activity. Instruction involved proper crutch and foot placement and cadence. The desired velocity of ambulation was 50 m/min to reduce the standard deviation of the group and to permit accurate comparisons

* Model 201-1, Rehabilitation Engineering Center No. 2, Moss Rehabilitation Hospital, 12th and Tabor Rd, Philadelphia, PA 19141.

† Warren E. Collins, 220 Wood Rd, Braintree, MA 02184.
‡ Beckman Instruments, Inc, 2500 Harbor Blvd, Fullerton, CA.
** Hewlett-Packard Co, 175 Wyman Rd, Waltham, MA 02154.

TABLE 2
Means and Standard Deviations of Physiological Values of Nonweight-Bearing and Touchdown Ambulation with Crutches

Variables	NWB	TD
$\dot{V}O_2$	16.65 ± 3.72	15.10 ± 3.21
Heart rate (beats/min)	140 ± 21[a]	131 ± 23
Systolic BP (mmHg)	136 ± 19	133 ± 17
Estimated $M\dot{V}O_2$[b]	20.36 ± 5.74[c]	18.09 ± 5.75

[a] Significant difference at $p < .01$.
[b] Estimated myocardial oxygen consumption expressed as ml $O_2 \cdot 100\ gm^{-1}$ of left ventricle.
[c] Significant difference at $p < .05$.

between gait sequences. The subjects participated in a mini-pilot sampling for one minute of NWB and of TD ambulation. This sampling was done to calculate the proper metronome settings for the 50 m/min velocity by measuring the subject's stride length for each mode of ambulation. After the sampling, the subject rested in a standing position for five minutes. We then measured resting $\dot{V}O_2$, HR, and SBP.

The performance order of the two experimental trials (NWB and TD ambulation) was randomly assigned. Each trial consisted of five minutes of ambulation with three minutes allowed for steady state to be reached. Expired air was collected for the fourth and fifth minutes. Heart rate was recorded each minute. Blood pressure was measured within the first 30 seconds after ambulation ceased. Subjective perception of exertion was assessed immediately after each trial. The number of times the subject traversed the walkway was recorded each minute to calculate velocity and step length. Between the two trials of ambulation, the subject rested in a standing position for a minimum of five minutes or until the HR returned to preambulation values.

Data Analysis

We analyzed the percent increase of $\dot{V}O_2$, HR, SBP, and $M\dot{V}O_2$ between resting and NWB and between resting and TD. Our second step was to perform a repeated measure analysis of variance (ANOVA) for the results of the experimental trials, but we did not include resting values in the ANOVA. We chose this means of analyzing the data for the following reasons:

1. Each subject had to return to resting values before each experimental trial.
2. The relevancy of the study lay in the difference between NWB and TD; we believe that clinicians do not commonly choose between resting and PWB but between types of PWB.

For the analysis of the Borg scale and the mechanical characteristics of each mode of ambulation, we determined the means and standard deviations.

RESULTS

Oxygen consumption, HR, SBP, step rate, and step length were analyzed. Myocardial oxygen consumption was estimated from HR alone and from RPP using the formula reported by Kitamura et al[5]:

$$M\dot{V}O_2 = 0.14 \times SBP \times HR \times 10^{-2} - 6.3 \qquad (1)$$

Data were compiled from the mean of the fourth and fifth minutes of rest or exercise. The data reflect the total mean for the 10 subjects tested.

Resting values were as follows: $\dot{V}O_2 = 3.45 \pm 0.58$ ml $O_2 \cdot kg^{-1} \cdot min^{-1}$; HR = 92 ± 18 beats/min; SBP = 119 ± 11 mmHg; and $M\dot{V}O_2 = 9.13 \pm 3.99$. The physiological findings for both experimental trials are outlined in Table 2. The percent increase in $\dot{V}O_2$, HR, SBP, and $M\dot{V}O_2$ from rest to NWB was 382, 52, 14, and 123, respectively. The percent increase in $\dot{V}O_2$, HR, SBP, and $M\dot{V}O_2$ from rest to TD was 332, 42, 12, and 98, respectively. Oxygen consumption was 10 percent higher during NWB than TD although the difference was not statistically significant. The difference in HR responses between the two modes of ambulation was significant ($p < .01$). The values for NWB were 7 percent higher than for TD. Systolic blood pressure was similar for both modes of ambulation. Rate-pressure product was significantly higher ($p < .05$) during NWB ambulation. A 13 percent difference occurred between the two modes of ambulation with NWB resulting in a greater RPP.

The subjects perceived NWB to be more strenuous than TD. Mean Borg scale responses were 14.00 ± 1.00 for NWB and 12.00 ± 1.00 for TD. Similar statistical comparisons were not imposed on this data because of the ordinal level of measurement.

A summary of the mechanical characteristics of each mode of ambulation can be found in Table 3. Subjects ambulated at the same velocities. The cadence required to maintain the velocity was significantly ($p < .05$) slower for NWB. Mean stride length was 6.7 percent greater during NWB than during TD, although the difference was not significant.

DISCUSSION

The velocity of NWB and TD ambulation was approximately 48 m/min and was comparable to self-selected velocity measurements obtained during restricted weight-bearing studies of normal and amputee subjects.[4,10] McBeath et al found self-selected velocity of 10 normal subjects to be 55.6 ± 13.2 m/min and 62.4 ± 16.0 m/min for 3-point PWB and NWB ambulation with crutches, respectively.[4] Oxygen consumption was determined to be 16 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ during NWB crutch ambulation in the present study. Cordrey et al[3] and McBeath et al[4] obtained values between 15 and 16 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$. Waters et al measured $\dot{V}O_2$ to be 16 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ in traumatic above knee amputees walking without a prosthesis at velocities similar to the velocity in this study.[10] The $\dot{V}O_2$ of TD ambulation was 15 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ in this investigation. Other investigators found that subjects consumed 10 to 11 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ during PWB ambulation.[3,4] Higher values in this study may have been the result of a clearer definition and more exact control of the percent-

TABLE 3
Means and Standard Deviations of Mechanical Values of Nonweight-Bearing and Touchdown Ambulation With Crutches

Variables	NWB	TD
Velocity (m/min)	48.42 ± 7.53	48.95 ± 7.19
Cadence[a] (step/min)	77 ± 11[a]	83 ± 10
Stride Length (m)	1.27 ± .22	1.19 ± .21

[a] Significant difference at $p < .05$.

age of weight allowed during ambulation. The low percentage of body weight used during TD may have contributed to the high $\dot{V}O_2$ values. Clinically, 10 percent of the body weight was comparable to NWB ambulation and, therefore, the most appropriate body weight for this study. Lastly, because subjects in this study did not ambulate at their self-selected velocity, $\dot{V}O_2$ may have increased.[10,11]

During crutch walking, a combination of concentric, eccentric, and isometric exercise is performed. Nonweight-bearing ambulation requires the muscles of the involved lower extremity to perform constant, sustained isometric contractions. The upper extremities must perform a sustained, isometric contraction during swing phase because neither lower extremity is touching the ground. Body weight is borne by the arms to the crutches. Touchdown ambulation requires a combination of isometric and isotonic exercise of the involved lower extremity as the involved leg moves in a normal heel to toe progression. In this study, 10 percent of body weight was placed on the involved lower extremity, and this reduced the amount of weight carried by the upper extremities compared with the amount of weight carried in NWB.

Oxygen consumption was not significantly different between the two modes of ambulation. Cordrey et al reported similar findings although the authors did not control velocity or weight bearing during their experiment.[3] Lind and McNicol found that $\dot{V}O_2$ for a combination of isometric and isotonic arm and leg exercise was contingent on the percentage of arm exercise contributing to the activity.[12] The percent difference in upper extremity work between NWB and TD may not have been adequate to make a significant difference in $\dot{V}O_2$. Both modes of ambulation commanded very high energy costs. The high rise in $\dot{V}O_2$ values above resting may have reflected the subjects' lack of proficiency at restricted weight-bearing ambulation. Imms et al conducted a five-week longitudinal study on the energy expenditure of crutch walking and found a significant decrease in $\dot{V}O_2$ over a period of time.[11] In addition, the physical condition of the subjects, such as their ability to perform upper extremity exercise, may have contributed to the high energy-cost values.[12]

Nonweight-bearing ambulation resulted in significantly higher HR than TD ambulation. Isometric exercise has been shown to result in a disproportionate increase in HR and SBP when compared with an equal amount of isometric work.[11,12] Lind and McNicol tested subjects as they performed isometric exercise at 20 percent to 50 percent of maximum voluntary contraction using arms, legs, and arms plus legs.[12] They found HR response to be related to percentage of maximum voluntary contraction and not to the size of the muscle. Significant rises in HR during NWB ambulation may have been caused by the greater percentage of isometric arm and leg exercise required during NWB versus TD ambulation.

Systolic blood pressure was found to be similar between the two forms of ambulation. Studies in the literature suggest a difference in SBP might have been anticipated.[12,13] Tuttle and Horvath[13] noted that SBP begins to fall toward resting values 15 seconds after exercise, and Lind and McNicol[12] found SBP returned to resting values after 60 seconds. In our investigation, SBP was measured within 30 seconds after terminating ambulation and isometric exercise. Thus, the difficulties in obtaining accurate, noninvasive SBP measurements during a mobility study and in clinical practice may have contributed to the lack of significance for this variable.

The double product of HR and SBP (RPP) and of HR alone have been shown to be a valid estimate of $M\dot{V}O_2$.[5] Although we found no difference in $\dot{V}O_2$, RPP and HR alone were significantly higher for NWB versus TD ambulation. This finding indicated a greater stress was imposed on the myocardium during NWB. The difference in $M\dot{V}O_2$ may be attributed to the greater isometric component present during NWB ambulation. In agreement with these findings, Greer et al found that RPP rose higher than $\dot{V}O_2$ values for isometric exercise.[14] Heart rate alone, as an indicator of $M\dot{V}O_2$, may be a more realistic gauge for clinicians.

Based on the Borg scale, subjects perceived NWB to be more strenuous than TD ambulation. These findings were obtained despite the subjects' lack of proficiency with either form of assisted ambulation. The difference in the perception of the exercises was verified by higher HR obtained during NWB. These findings are in agreement with the findings of Borg.[6]

Physiologically, both modes of ambulation can be considered highly stressful. Oxygen consumption rose 332 to 382 percent, HR rose 42 to 53 percent, SBP rose 12 to 14 percent, and estimated $M\dot{V}O_2$ rose 98 to 123 percent from rest to assisted ambulation. Thus, initial training with either mode of ambulation is extremely stressful although it could be expected to decrease somewhat with practice. Special considerations for prescription and training should be given to the patient with limited functional capacity, such as sedentary or deconditioned individuals and patients with cardiovascular disease. Based on myocardial work, TD ambulation may be preferable to NWB ambulation. We recommend that this study be repeated on geriatric individuals and persons with limited functional work capacities. In addition, it would be beneficial to compare the procedure for free cadence versus controlled velocities.

CONCLUSION

We found oxygen consumption to be similar for NWB and TD ambulation at a given velocity. Estimates of $M\dot{V}O_2$ (RPP and HR alone) were higher during NWB ambulation, which was attributed to the larger percentage of upper and lower extremity isometric exercise required for NWB ambulation. Systolic blood pressure was similar for both modes of ambulation and was attributed to the experimental design. Lastly, subjects perceived NWB ambulation to be subjectively more stressful than TD ambulation. Physiologically, TD ambulation was less stressful to the cardiovascular system than NWB ambulation.

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