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ORIGINAL ARTICLE

Cardiovascular responses in older adults with total knee arthroplasty at rest and with exercise on a positive pressure treadmill

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Abstract
Purpose We investigated cardiovascular responses at rest and during submaximal exercise on a lower body positive pressure treadmill in older adults with total knee arthroplasty (TKA).
Methods Twenty-four adults (mean age 64.6 ± 7.9 SD) with unilateral TKA participated (median time since surgery 8.0 weeks). Heart rate and blood pressure responses were measured at rest standing on the positive pressure treadmill with 0, 10, 20, and 30 mmHg applied. Heart rate, blood pressure, oxygen consumption, minute ventilation, knee pain and perceived exertion were measured during submaximal exercise tests (0 and 40 % body weight support) conducted 1 week apart.
Results At rest there were no differences in blood pressure across different treadmill pressures, but heart rate was significantly lower when 30 mmHg was applied compared to ambient pressure conditions ($P < 0.05$). Participants averaged 5.1 exercise test stages with 0 % body weight support (maximum speed 2.5 mph, 0 % incline) and 6.4 stages with 40 % body weight support (maximum speed 3.0 mph, 10 % incline). During exercise, heart rate, systolic blood pressure, oxygen consumption, and minute ventilation were lower when 40 % body weight support was provided for a given test stage ($P < 0.01$). Diastolic blood pressure, knee pain and perceived exertion did not differ with body weight support but increased with increasing exercise test stages ($P < 0.05$).
Conclusions Provision of body weight support allowed TKA patients to walk at faster speeds and/or to tolerate greater incline with relatively lower levels of heart rate, blood pressure, and oxygen consumption.

Keywords Blood pressure · Exercise test · Heart rate · Walking

Abbreviations

ANOVA	Analysis of variance
bpm	Beats per minute
ECG	Electrocardiogram
IQR	Interquartile range
KOS-ADL	Knee Outcome Survey Activities of Daily Living Scale
mph	Miles per hour
SCT	Stair climb test
SD	Standard deviation
TKA	Total knee arthroplasty
TUG	Timed-up-and-go test
VO_2	Oxygen consumption

Introduction

Providing partial body weight support for ambulation through the use of parallel bars, walkers, crutches, therapeutic pools, and overhead suspension harnesses is fundamental for rehabilitation when full weight bearing is contraindicated because of pain, weakness, and/or limitations

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in bone or joint loading capabilities. Treadmills with suspension harnesses have typically been used to provide gait retraining and aerobic exercise for patients with neurological (Knikou 2012; Miyai et al. 2000; Moseley et al. 2005; Mutlu et al. 2009; Valentin-Gudiol et al. 2011) and orthopedic conditions (Di et al. 2009; Joffe et al. 2002; Mangione et al. 1996) and have also been used to promote safe walking for frail older adults (Thomas et al. 2011) and those living in assisted-living facilities (Johnson et al. 2013). While harness systems increase safety and allow individuals with many types of gait impairments to use a treadmill, some research suggests that lower extremity kinematics and/or kinetics (Decker et al. 2012; Lewek 2011; Millslagle et al. 2006) may be altered when a harness is used and many patients find a harness uncomfortable (Ruckstuhl et al. 2009).

Lower body positive pressure treadmills offer an alternative method for body weight-supported walking by providing a positive pressure chamber which surrounds the individual's lower body and the treadmill. Computer-regulated air pressure creates a buoyant force (proportional to the pressure differential between the inside and outside of the chamber multiplied by the cross-sectional area of the user's lower body and the flexible waist seal on the chamber) which reduces the net ground reaction force and effectively allows patients to ambulate under less than full body weight conditions (Cutuk et al. 2006; Patil et al. 2013). To date, there have been no large-scale intervention trials using lower body positive pressure treadmills, however, they have been tested in healthy individuals (Cutuk et al. 2006; Grabowski 2010; Ruckstuhl et al. 2009, 2010), athletes (Gojanovic et al. 2012) and patients with a variety of conditions including cerebral palsy (Kurz et al. 2011), arthroscopic meniscectomy (Eastlack et al. 2005), anterior cruciate ligament reconstruction (Eastlack et al. 2005), osteoarthritis (Takacs et al. 2013), lumbar disc herniation (Moore et al. 2010) and Parkinson's disease (Rose et al. 2013a, b). Preliminary results suggest that gait kinematics and muscle activation are not substantially affected by lower body positive pressure, unless 75 % or greater body weight support is provided (Cutuk et al. 2006; Eastlack et al. 2005; Grabowski 2010).

Although lower body positive pressure treadmills can provide finely gradated, comfortable body weight support, it has been demonstrated that applying positive air pressure through a lower body chamber has the potential to influence physiological responses. The nature and extent of physiological change depends on the degree of pressure utilized, the posture of the individual (e.g., supine or upright) and activity level (e.g., at rest or during exercise) (Nishiyasu et al. 1998, 2007). Studies conducted on individuals at rest in an upright position have generally demonstrated that the addition of lower body positive pressure (25–75 mmHg) results in an elevation in mean arterial pressure, stroke volume, cardiac output and total vascular conductance (Nishiyasu et al. 1998, 2007), whereas heart rate levels are reduced (Cutuk et al. 2006; Hoffman and Donaghe 2011; Nishiyasu et al. 1998, 2007). It is believed that these physiological changes occur because of the shift in blood volume from the lower body to the trunk with the application of lower body positive pressure. The resulting increased venous return triggers the high-pressure baroreceptors which then cause a reduction in heart rate and increased vasodilation in the periphery (Nishiyasu et al. 2007). Investigations with participants in the supine position have demonstrated even greater increases in mean arterial pressure compared to those seen in upright postures (Nishiyasu et al. 1998) which may be produced by other mechanisms such as activation of intramuscular pressure-sensitive receptors (Shi et al. 1993).

Heart rates have also been shown to be lower for a given workload during walking in positive pressure conditions (Cutuk et al. 2006; Ruckstuhl et al. 2009, 2010) and unchanged during upright cycling (Nishiyasu et al. 1998) and semi-recumbent cycling (Williamson et al. 1994, 1996) in a lower body positive pressure chamber. Whereas positive pressures of 25 mmHg or greater have been shown to increase mean arterial pressure during upright cycling (Nishiyasu et al. 1998) and recumbent cycling (Williamson et al. 1994, 1996), it is unclear whether similar blood pressure responses occur with walking on a positive pressure treadmill. To date, only one study has investigated blood pressure responses with walking in lower body positive pressure conditions (Cutuk et al. 2006). Cutuk and colleagues (2006) reported that positive pressure levels ranging from 20 to 50 mmHg resulted in slightly higher resting systolic and diastolic blood pressure levels during walking, however, the changes did not reach statistical significance in their sample of nine adults.

Research to date examining cardiovascular responses with the use of these treadmills has primarily included younger healthy individuals and relatively small samples sizes ranging from 8 to 10 participants (Cutuk et al. 2006; Ruckstuhl et al. 2010). However, the unloading system provided by a lower body positive pressure treadmill could benefit older adults with a wide variety of musculoskeletal and neurological conditions. Because older individuals typically have higher resting blood pressures and decreased reactivity of baroreceptors compared to younger people (Cheitlin 2003; Monahan 2007), it is important to determine cardiovascular responses to using lower body positive pressure in this age group. In addition, further research is required to better understand metabolic demands, and changes in walking tolerance using lower body positive pressure to determine its efficacy for use in clinical situations. We were interested in studying these parameters in older individuals who had recently undergone total knee arthroplasty (TKA) because body weight supported ambulation would be relevant in the rehabilitation of these patients who frequently have significant levels of pain that may limit mobility post-surgery.

The primary objective of this study was to determine cardiovascular responses at rest and with walking under lower body positive pressure conditions in older adults with TKA. Secondarily, we were interested in examining metabolic responses, walking tolerance, and pain ratings when body weight support was provided to better understand the feasibility of using a lower body positive pressure treadmill in the rehabilitation of these patients.

Methods

Participants

Patients 50–80 years of age who had recently undergone unilateral TKA for osteoarthritis were recruited for the study. We were primarily interested in testing patients 6–12 weeks post-operatively who were able to walk without a walking aid but still demonstrated limited tolerance to prolonged walking. Individuals who reported being able to walk for 5–10 min at a slow pace without a walking aid were eligible and those who were able to walk >10 min at a self-reported moderate or fast past were excluded. The median time since surgery for our participants was 8.0 weeks [interquartile range (IQR), 25th percentile–75th percentile = 7.5–10.5 weeks]. Potential participants were excluded if they had a previous TKA or if they were planning to have contralateral knee surgery in the next 6 months. In addition, individuals who rated their knee pain >6 on a 10-point scale, were taking beta-blocker medication or had conditions that limited safe participation in physical activity were not eligible to participate. The Biomedical Research Ethics Board of the University of Saskatchewan granted ethical approval for this study, and participants provided written informed consent prior to any data collection.

This study used a randomized cross-over design. Eligible participants attended three visits, each 1 week apart, at the same time of day. On the first visit, participants completed questionnaires and baseline testing. Physiological responses to lower body positive pressure were measured at rest, and then participants were familiarized to walking on the AlterG M320 anti-gravity treadmill (AlterG, Fremont, CA). On the subsequent two visits, submaximal graded exercise tests were conducted on the AlterG treadmill at 0 and 40 % body weight support. The order of testing (0 and 40 % body weight support) was randomized.

Baseline testing

At the first visit, a demographic and health questionnaire was completed along with the Knee Outcome Survey Activities of Daily Living Scale (KOS-ADL) (Irrgang et al. 1998) which is used to assess patient-reported functional limitations caused by knee pathology and impairment during activities of daily living. Higher scores indicate higher levels of function with the highest possible score being 70. Body mass and height were recorded and knee active range of motion was measured with a goniometer.

Functional testing included the Timed-up-and-go test (TUG), stair climb test (SCT) and a timed 100 m walk. The TUG was completed over a walking distance of 3 m, using a chair with armrests and a seat height of 46 cm. The TUG has been shown to be reliable, and to have functional content validity in measuring basic functional mobility in older adults post-TKA (Boonstra et al. 2008; Kennedy et al. 2005). Each participant performed two trials at a normal pace but only the second trial was recorded. Participants were then timed as they ascended and descended a flight of nine stairs (step height 16.5 cm, depth 26.0 cm). Ascending and descending times were recorded separately. Longer times for the SCT have been shown to indicate poorer function (Bennell et al. 2010). To determine gait speed and gage walking tolerance, participants were timed as they walked 100 m (Phan-Ba et al. 2011).

Physiological responses at rest

After baseline testing was completed, participants were asked to stand on the AlterG anti-gravity treadmill for a total of 12 min. Every 3 min, an additional 10 mmHg pressure was added to the treadmill's chamber such that pressure levels were 0, 10, 20, and 30 mmHg. Because the AlterG M320 treadmill system only displays body weight support in units of percent body weight (which would result in different absolute pressure levels among participants), pressure inside the treadmill chamber was set to 0, 10, 20, and 30 mmHg as measured with an Omega HHP-90 handheld digital pressure meter (OMEGA Engineering Inc., Laval, QC) for this component of testing. A Propaq CS monitor (Welch Allyn, Skaneateles Falls, NY) was used for monitoring heart rate and blood pressure while participants were on the treadmill using a 3-electrode electrocardiogram (ECG, modified V5 lead) and the automated blood pressure monitor. Blood pressure was measured during the final 45 s of each 3 min stage and heart rate was noted in the last 10 s of the stage. Upon completion of the fourth stage of testing, participants walked on the treadmill for approximately 10 min to become familiar with different speeds and levels of body weight support. They were also encouraged to try wearing the headgear and mouthpiece

Table 1 Treadmill speed and incline levels for stages of submaximal exercise test (mean ± SD)

Exercise test stage	40 % Body weight support			0 % Body weight support		
	Participants	Speed (mph)	Incline (%)	Participants	Speed (mph)	Incline (%)
1	23	0	0	23	0	0
2	23	1.47 ± 0.45	0	23	1.47 ± 0.45	0
3	23	1.97 ± 0.45	0	22	1.97 ± 0.46	0
4	23	2.47 ± 0.45	0	21	2.47 ± 0.47	0
5	23	2.71 ± 0.42	2.17 ± 2.53	18	2.81 ± 0.41	2.50 ± 2.57
6	19	2.86 ± 0.37	6.32 ± 4.36	7	3.04 ± 0.36	7.14 ± 3.93
7	12	3.03 ± 0.42	10.91 ± 5.39	2	2.90 ± 0.14	10.00 ± 7.07
8	1	3.50	15.00	–	–	–

associated with the ParvoMedics TrueOne 2400 Metabolic Measurement System (ParvoMedics, Sandy, UT) so that it would be familiar for use during the submaximal graded exercise tests in sessions 2 and 3.

Submaximal exercise testing

Submaximal graded exercise tests using 4 min stages were conducted on the AlterG anti-gravity treadmill with 0 and 40 % body weight support during sessions 2 and 3. We chose to investigate parameters at 40 % body weight support because this represented an appreciable but not excessive level of support for individuals recovering from TKA. In addition, the use of 40 % body weight support (Cutuk et al. 2006; Ruckstuhl et al. 2009, 2010) and 4 min stages (Hoffman and Donaghe 2011) allowed for comparisons with previous work. The order of testing was randomized (in blocks of six participants) such that 12 participants were first tested at 0 % body weight support and 11 were first tested at 40 % body weight support. Prior to initiating testing, participants were familiarized with the Borg 0-to-10 point Rating of Perceived Exertion Scale (Borg 1998) and a 0-to-10 point numeric pain rating scale. On the numeric pain rating scale, 0 corresponded to no pain, 1–3 with mild pain, 4–6 with moderate pain and 7–10 with severe pain. During testing, heart rate and rhythm were monitored continuously using the Propaq CS (modified V5 ECG lead). Heart rate for each stage was noted in the last 10 s of each 4 min stage. Blood pressure was measured manually, always by the same tester using the same sphygmomanometer and stethoscope during the last minute of each stage. Participants were also asked to report perceived exertion and knee pain in the last 30 s of each stage. Oxygen consumption, respiratory rate and minute ventilation were measured continuously with the ParvoMedics TrueOne 2400 Metabolic Measurement System (calibrated prior to each test). Values recorded in the last minute of each stage were averaged to obtain a representative value for each stage. Baseline resting measures were gathered during the first stage of the test (speed and incline set to zero, 20 % body weight support). Some (20 %) body weight support was provided for this first stage so that participants experienced a change in body weight support (adjusted down to 0 % or up to 40 %) for both protocols in an attempt to blind them to which protocol was being used. The pressure then remained constant for the remainder of the test. The AlterG display panel was covered during all stages of the exercise tests so that the degree of body weight support could not be read by the participants.

The initial treadmill walking speed varied for participants, depending on comfortable walking speeds identified during the initial individual familiarization session ($n = 3$ at 0.8 mph, $n = 5$ at 1.0 mph, $n = 9$ at 1.5 mph, $n = 5$ at 2.0 mph, $n = 1$ at 2.5 mph). Incline was always initially set at 0 % and speed increased by 0.5 mph per stage. A 5 % incline was introduced if the participant reached their maximum comfortable walking speed but did not yet meet criteria to discontinue the walking test. If additional stages were required, a further 5 % incline was added. Once incline was introduced there were no further increases in speed. The majority of participants (18/23) were able to complete additional stages when 40 % body weight support was provided. Table 1 provides mean ± SD values for treadmill speeds and incline levels experienced for each stage during the submaximal exercise tests. End-points for the submaximal tests included symptom limitation ($n = 19$), change in knee pain rating $\geq$4/10 from resting value ($n = 11$), rating of perceived exertion $\geq$7/10 ($n = 2$), heart rate $\geq$85 % age-predicted maximum ($n = 11$), exaggerated systolic response ($n = 2$), and arrhythmia ($n = 1$).

Statistical analyses

Statistical analyses were conducted using SigmaPlot (Version 11.0, Systat Software, Inc., San Jose, CA) and Statistica (Version 10, StatSoft, Inc., Tulsa, OK). All continuous data were assessed for normality. Normally distributed variables are reported as means (SD) and non-normally distributed variables are reported as medians (IQR). Nonparametric tests were used when assumptions were violated for parametric testing.

Using $\alpha = 0.05$ and power = 0.80, it was estimated that 20 participants were needed to demonstrate significant differences in cardiovascular and metabolic parameters in response to lower body positive pressure. The calculation was based on results reported by Ruckstuhl and colleagues from studies involving younger individuals (Ruckstuhl et al. 2009, 2010). They demonstrated that oxygen consumption decreased by 10 % (SD 8 %) and 8 % (SD 10 %) at slow (0.4 m s^{-1}) and comfortable walking speeds (1.3 m s^{-1}), respectively, when positive pressure was used to provide 0 and 34 % body weight support (Ruckstuhl et al. 2010). Heart rates reduced by 8 % (SD 11 %) and 6 % (SD 9 %) under the same conditions. In a separate study (also evaluating younger people), the same researchers reported that heart rate declined from 99 bpm (beats per minute, SD 15) to 88 bpm (SD 14) when 34 % body weight support was provided (Ruckstuhl et al. 2009).

To determine whether changes in lower body positive pressure under static (standing) conditions affected heart rate, systolic blood pressure, and diastolic blood pressure, one-way ANOVA and Kruskal–Wallis one-way ANOVA on ranks tests were used for parametric and non-parametric data, respectively. When differences were detected, Dunnett's multiple comparison test was used to compare values at each pressure level (10, 20, 30 mmHg) to the baseline (ambient pressure) condition.

Paired *t* tests and Wilcoxon signed rank tests were used to compare the number of stages completed under the 0 and 40 % body weight support conditions as well as the cardiovascular and metabolic responses obtained in the final stages. To determine the effect of test order, body weight support, and exercise test stage on physiological and perceived responses during the submaximal walking tests, a series of three-way ANOVA tests with two repeated measures were conducted ($P < 0.05$). Test order was treated as an independent factor; level of body weight support, and exercise test stage (1–5) were the repeated measures. Attempts to include data from more than five stages resulted in excessive missing data (e.g., only seven participants completed six exercise test stages at 0 % body weight support, see Table 1), therefore, only data from the first five stages were included in analyses. Dependent variables included: heart rate, systolic blood pressure, diastolic blood pressure, oxygen consumption, knee numeric pain rating, perceived exertion, and minute ventilation. The result of the three-way interaction was initially examined, followed by results of the three two-way interactions and the main effects for each test. None of the three-way interaction terms were found to be significant and the main effect for test order was also not significant for any of the tests. When the two-way interaction term for level of body weight support by exercise test stage was significant, post hoc paired *t* tests (and Wilcoxon signed rank tests when data were not normal) were conducted to compare results at 0 and 40 % body weight support at each exercise stage. Because five within-group comparisons were made, the significance level was set at 0.01 (0.05/5) for these analyses. When the main effect of exercise stages was significant, a Kruskal–Wallis one-way ANOVA on ranks was conducted with Dunn's multiple comparison test used to detect differences at each stage relative to rest (stage 1).

Table 2 Participant demographics and baseline test results

	Mean (SD) or median (IQR)
Age (years)	64.6 ± 7.9
Body mass (kg)	83.4 (75.8−95.5)
Body height (cm)	168.5 ± 7.5
Body mass index (kg m^{-2})	29.9 (27.1−32.3)
Weeks post-surgery	8.0 (7.5−10.5)
Gait speed (100 m walk, m s^{-1})	1.2 ± 0.3
Stair time ascending (s)	6.7 (6.1−8.8)
Stair time descending (s)	7.2 (5.7−9.1)
Timed-up-and-go (s)	9.5 ± 2.1
Active knee flexion (°)	105.7 ± 11.1
Active knee extension (°)	−10 [−14.5−(−7.5)]
KOS-ADL Scores	45.5 + 10.4

Results

Twenty-four individuals (12 women and 12 men, mean age 64.6 ± 7.9 SD) participated in this study. One participant only completed baseline and resting tests because a cardiac arrhythmia was detected with ECG. Demographic information and results of baseline tests conducted during the initial session are presented in Table 2. Heart rate, systolic blood pressure and diastolic blood pressure readings recorded during the 3 min stationary standing stages are presented in Table 3. There were no significant differences in systolic or diastolic blood pressures with different levels of pressure (one-way ANOVA, $P = 0.83$ and $P = 0.92$, respectively). Median heart rates differed across pressure levels (one-way ANOVA on ranks, $P = 0.04$) such that heart rates measured under 30 mmHg pressure conditions were significantly lower than those recorded under ambient pressure conditions (Dunnett's multiple comparison test, $P < 0.05$).

The mean lower body positive pressure measured when 40 % body weight support was provided by the AlterG treadmill was 18.3 ± 3.2 mmHg. Pressure in the chamber was 1.0 ± 0.1 mmHg when no body weight support was provided and 9.2 ± 1.5 mmHg when 20 % support was provided (for exercise test stage 1 when resting measurements were taken). On average, participants were able to

Table 3 Cardiovascular responses at rest in lower body positive pressure treadmill

Pressure (mmHg)	Heart rate [median (IQR), bpm]	Systolic blood pressure (mean ± SD, mmHg)	Diastolic blood pressure (mean ± SD, mmHg)
0	84.0 (72.5–94.0)	124.8 ± 21.2	66.9 ± 10.6
10	80.0 (71.5–90.0)	123.3 ± 17.7	68.6 ± 9.9
20	76.5 (68.0–85.5)	127.8 ± 15.8	68.5 ± 9.7
30	71.0 (65.5–83.0)*	127.0 ± 16.7	68.6 ± 8.9

bpm beats per minute

* Significantly different from heart rate measured under ambient pressure conditions ($P < 0.05$)

complete at least one additional stage when 40 % body weight support was provided compared to 0 % body weight support (Table 4). The final maximum speed and incline settings were significantly higher and heart rate, oxygen consumption (VO_2) and minute ventilation were significantly reduced when body weight support was provided.

The exercise test stage by body weight support level two-way interaction was significant for each of the following variables: heart rate, systolic blood pressure, minute ventilation, and VO_2. Post hoc tests demonstrated significantly higher heart rate, minute ventilation and VO_2 values at all exercise test stages (i.e., stages 2–5 as stage 1 values were recorded in the initial resting stage) for the 0 % body weight support condition compared to 40 % body weight support (Fig. 1, all comparisons $P < 0.01$). Systolic blood pressure was significantly higher when 0 % body weight support was provided for exercise test stages 2, 3, and 5 ($P < 0.01$, Fig. 1).

For diastolic blood pressure, knee pain and rating of perceived exertion, the main effect for exercise stage was significant ($P < 0.001$). Diastolic blood pressure and numeric pain rating were higher for stages 4 and 5 compared to resting values obtained in stage 1 (Fig. 2, $P < 0.05$). Ratings of perceived exertion were greater at all exercise stages compared to rest (Fig. 2, $P < 0.05$).

Discussion

Walking with 40 % body weight support allowed older adults post-TKA to walk at faster speeds and/or to tolerate greater incline compared to walking without body weight support. For a given speed/incline, walking with 40 % body weight support resulted in lower heart rate, systolic blood pressure, oxygen consumption and minute ventilation levels. However, despite the different metabolic requirements and cardiovascular responses associated with unweighting, there were no significant differences in perceived exertion or knee pain ratings which were greater with later exercise test stages when both 0 and 40 % body weight support were provided. The reduced lower extremity loading and lower metabolic demands associated with body weight support allowed patients to walk faster and/or tolerate increased incline without increased complaints of pain or increased levels of perceived exertion. This may be important in the rehabilitation of TKA patients and individuals with other conditions when the primary goal is to improve walking ability as opposed to engaging in moderately vigorous intensity aerobic exercise.

Using lower body positive pressure to reduce the net ground reaction force and allow ambulation under body weight supported conditions reduces the metabolic cost of activity and changes cardiovascular responses. Changes in cardiovascular responses occur as a combined result of the reduced metabolic demands of activity and in response to the addition of positive pressure to the lower body. Research conducted on individuals at rest in a seated or standing position has generally demonstrated elevations in mean arterial pressure, stroke volume, cardiac output and

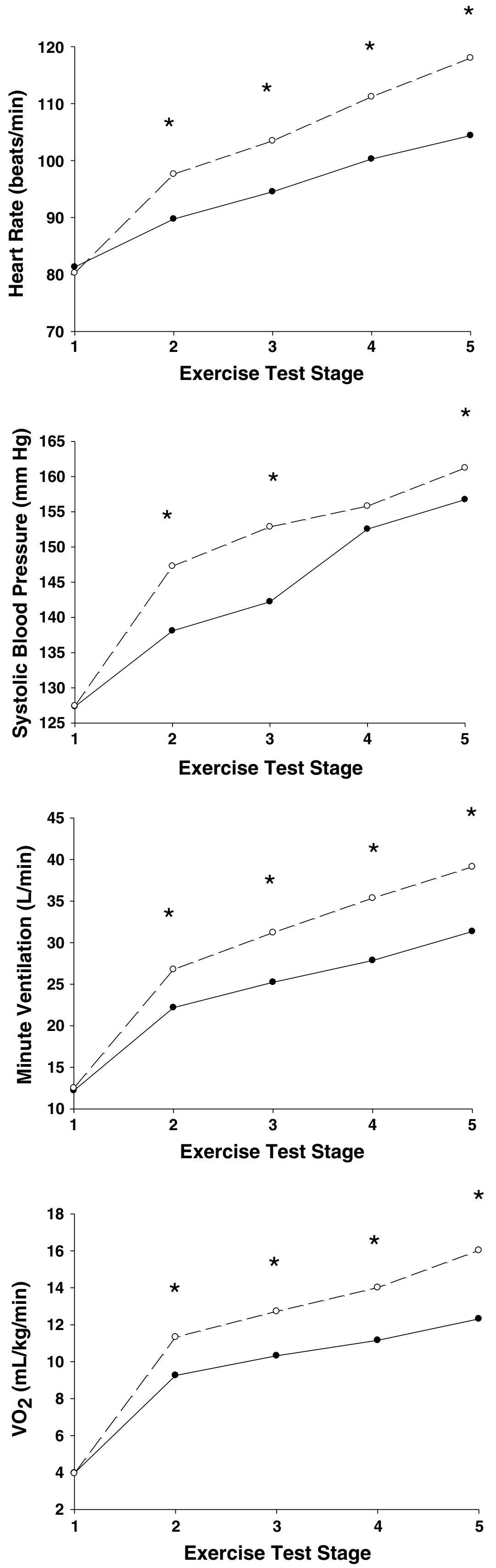
Table 4 Final exercise test stages [mean ± SD or median (IQR)]

	0 % Body weight support	40 % Body weight support	P value
Number of stages completed[a]	5.1 ± 1.2	6.4 ± 0.8	$P < 0.001$
Maximum speed (mph)[b]	2.5 (2.5–3.0)	3.0 (2.5–3.0)	$P = 0.031$
Maximum incline[b]	0.0 (0.0–5.0)	10.0 (0.0–15.0)	$P < 0.001$
Knee pain rating[b]	3.0 (1.0–3.0)	2.0 (1.3–3.8)	$P = 0.455$
Rating of perceived exertion[b]	4.0 (4.0–5.0)	4.0 (3.0–4.8)	$P = 0.147$
Heart rate achieved (bpm)[a]	122.6 ± 17.8	110.5 ± 13.3	$P < 0.001$
VO_2 (mL kg^{-1} min^{-1}) achieved ($n = 20$)[a]	16.3 ± 2.7	13.5 ± 1.8	$P < 0.001$
Systolic blood pressure (mmHg)[a]	162.7 ± 23.5	159.9 ± 24.4	$P = 0.296$
Minute ventilation (L min^{-1})[a]	41.9 ± 9.1	34.7 ± 7.8	$P < 0.001$
Diastolic blood pressure (mmHg)[a]	84.0 ± 7.9	83.7 ± 7.7	$P = 0.857$
Respiratory rate (min^{-1})[a]	30.6 ± 6.3	29.0 ± 6.8	$P = 0.161$

mph miles per hour; $n = 23$ unless otherwise indicated

[a] Paired *t* test

[b] Wilcoxon signed rank test



◀**Fig. 1** Responses for each exercise test stage (*filled circle* = 40 % body weight support, *opened circle* = 0 % body weight support, *asterisk* significantly different between exercise test conditions $P < 0.01$)

total vascular conductance (Nishiyasu et al. 1998, 2007), and reduced heart rates (Cutuk et al. 2006; Hoffman and Donaghe 2011; Nishiyasu et al. 1998, 2007). In contrast, the addition of lower body positive pressure to upright and semi-recumbent cycling has been shown to result in elevations in mean arterial pressure with no changes in heart rate (Nishiyasu et al. 1998; Williamson et al. 1994, 1996). A primary difference between walking/running on a lower body positive pressure treadmill and being exposed to lower body positive pressure during cycling relates to the fact that walking/running involves weight bearing and adding positive pressure to a treadmill chamber results in the reduction of ground reaction forces and metabolic demands of the activity (Raffalt et al. 2013). Cycling under ambient and lower body positive pressure conditions has been shown to result in similar oxygen consumption levels (Nishiyasu et al. 1998), whereas oxygen consumption measurements have been shown to be reduced when individuals walk or run on a lower body positive pressure treadmill (Hoffman and Donaghe 2011; Raffalt et al. 2013; Ruckstuhl et al. 2010).

In our study of older adults walking on a lower body positive pressure treadmill, the cardiovascular parameters of heart rate and blood pressure were measured. Individuals demonstrated reductions in heart rates ranging from 7.8 to 12.4 % across exercise test stages 2–5 when 40 % body weight support was provided compared to full body weight conditions. These results are similar to those reported in younger people (Cutuk et al. 2006; Ruckstuhl et al. 2009). Ruckstuhl and colleagues (2009) measured heart rate during slow, comfortable, and fast paced walking on a lower body positive pressure treadmill in 12 healthy younger volunteers when 0 and 34 % body weight support was provided. Reductions in heart rate were approximately 7 % at slow walking speeds and 11 % at comfortable walking speeds. Cutuk and colleagues (2006) found that walking on the treadmill at 3 mph resulted in a significant reduction in heart rate from 99 bpm in ambient pressure conditions to 84 bpm when 50 mmHg was applied. Based on these comparisons, older and younger adults appear to demonstrate similar heart rate responses with walking under lower body positive pressure conditions. These reductions in heart rate may be related to baroreceptor stimulation in response to increased venous return caused by the lower body positive pressure; however, the reduced metabolic cost of walking in a partial body weight supported condition may play an even greater role in reducing heart rate.

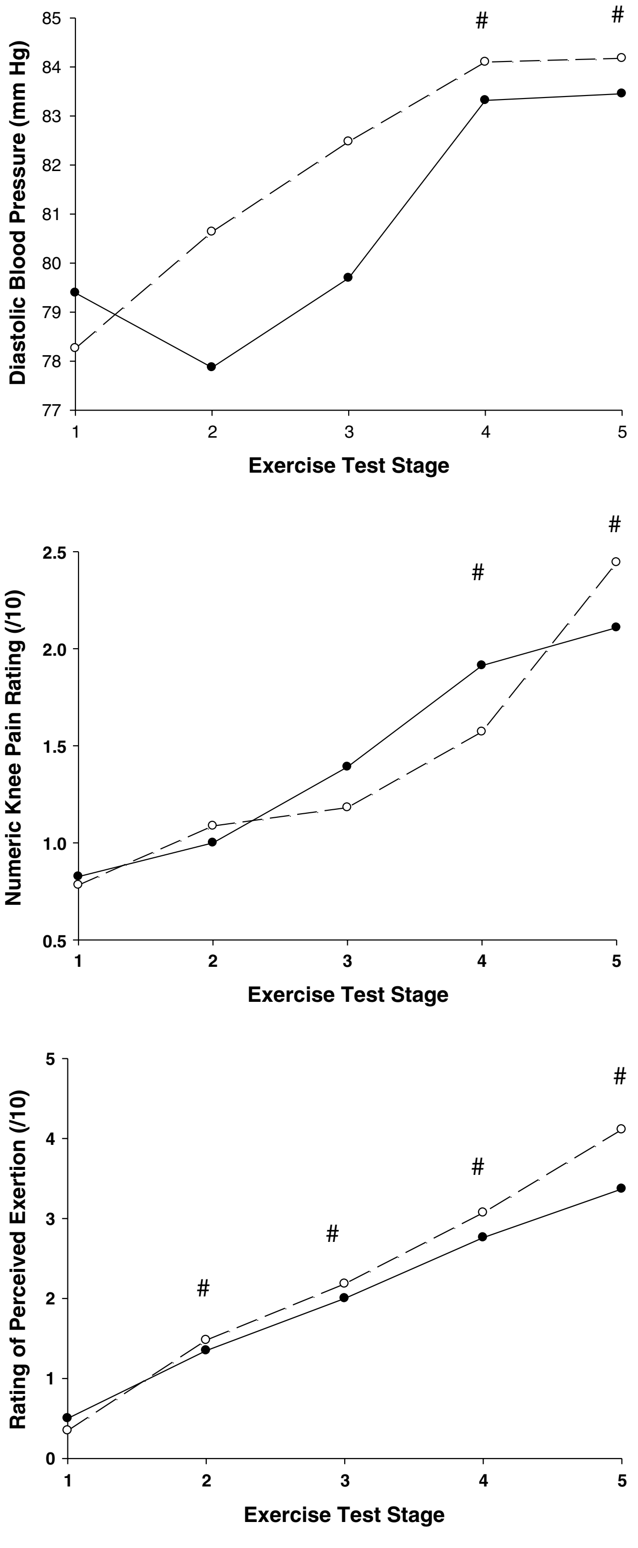


Fig. 2 Responses for each exercise test stage (*filled circle* = 40 % body weight support, *opened circle* = 0 % body weight support, *ash symbol* significantly different from stage 1 resting values $P < 0.05$)

Participants also demonstrated small reductions in systolic blood pressure ranging from 3.4 to 6.8 % when 40 % body weight support was provided during walking. This is in contrast to Cutuk and colleagues (2006) who found non-significant trends for increases in systolic and diastolic blood pressure with walking on the positive pressure treadmill. These differences, although small, deserve further investigation as to date these represent the only two studies to report blood pressure responses with walking on a lower body positive pressure treadmill. The differences in results may be related to differences in the ages of participants (mean age was 65 in the current study versus 22–55 years of age in Cutuk et al.'s study), variations in the relative metabolic cost of workloads and the specific testing protocols utilized. Cutuk and colleague's protocol involved walking at a constant speed of 3 mph with heart rate and blood pressure measurements recorded after 1 min at each of the pre-determined pressure levels (0, 25, 50 mmHg presented in random order), whereas participants in the current study were given a minimum of 3 min to reach a steady exercise state (American College of Sports Medicine 2013) at each test stage before measurements were taken. In addition, the mean pressure required to provide 40 % body weight support was just 18.3 ± 3.2 mmHg for participants in our study, substantially lower than the levels of 25 and 50 mmHg used by Cutuk and colleagues. While studies involving upright cycling (Nishiyasu et al. 2007) and recumbent cycling (Williamson et al. 1994, 1996) under lower body positive pressure conditions have reported increases in mean arterial pressure, similar responses may not occur with ambulation on a positive pressure treadmill because the metabolic demands associated with walking (a weight-bearing activity) are decreased when positive pressure is added.

In conjunction with reduced heart rate and systolic blood pressure levels associated with 40 % body weight supported walking, our participants also demonstrated reductions in oxygen consumption ranging from 17.7 to 23.1 % across exercise test stages. In comparison, Ruckstuhl and colleagues (2010) noted non-significant 8–10 % reductions in oxygen consumption during walking and significant 26–28 % reductions with running under low body positive pressure conditions. It has been previously demonstrated in healthy younger active adults that body weight support decreases oxygen consumption requirements more substantially for running compared to walking (Hoffman and Donaghe 2011). Our post-TKA participants achieved moderate physical activity intensities with the submaximal walking tests which likely were sufficiently metabolically challenging such that 40 % body weight support substantially reduced oxygen consumption requirements. Interestingly, in our study and in the younger healthy participants evaluated by Ruckstuhl (2010), ratings of perceived exertion did not change with the addition of lower body positive pressure when participants exercised at walking speeds. Ruckstuhl and colleagues did demonstrate that ratings of perceived exertion were 6–11 % lower during running when 34 % body weight support was provided, however, differences in ratings of perceived exertion were not significant at the slower (walking) speeds (0.4 and 1.3 m s^{-1}). These results suggest that there may be a threshold associated with the reduced oxygen consumption induced by the application of lower body positive pressure (e.g., 25 % reduction in oxygen consumption) which must be exceeded to have an appreciable effect on ratings of perceived exertion. The magnitude of this threshold may vary for participants with different ages and/or chronic conditions.

In addition to the exercise tests, we monitored cardiovascular responses at rest when participants stood in the AlterG treadmill and progressive levels of positive pressure were applied. Median heart rates were significantly lower when 30 mmHg was applied (71 bpm) compared to ambient pressure (84 bpm). Cutuk and colleagues (2006) similarly noted reductions in heart rate ranging from 8 to 13 bpm when pressures $\geq$20 mmHg were applied during standing, and Hoffman and colleagues (2011) found significant reductions of 7 bpm when 50 % body weight support was provided. In both our study and the one conducted by Cutuk and colleagues, systolic and diastolic blood pressure levels increased with increasing treadmill chamber pressure levels, but the changes in blood pressure were not statistically significant. While Hoffman's group found no significant change in diastolic blood pressure, systolic blood pressures increased significantly from 117 mmHg in ambient conditions to 127 mmHg when 50 % body weight support was provided in standing. The results of these three studies suggest that small and sometimes more substantial increases in blood pressure can occur during standing with the application of lower body positive pressure. However, changes in blood pressure responses during exercise are likely more important and deserve further investigation to determine the relationships among blood pressure, treadmill chamber pressure, and relative intensity of physical activity.

Previous studies have determined that using a lower body positive pressure treadmill can effectively lower the forces acting on the lower extremities (Cutuk et al. 2006; Eastlack et al. 2005; Hoffman and Donaghe 2011; Patil et al. 2013), yet participants in this study did not report any significant differences in knee pain ratings when 0 and 40 % body weight support were provided during the submaximal walking tests. A previous study also found little difference in knee pain ratings with ambulation at 0, 40 and 80 % body weight support in patients who had undergone arthroscopic menisectomy (Eastlack et al. 2005). The menisectomy patients reported little pain regardless of the amount of body weight support provided, which was similar to TKA patients in our study. Use of the lower body positive pressure treadmill earlier in the post-operative period may have resulted in more substantial differences in pain ratings when body weight support was provided. However, pain experienced after TKA is often associated with knee flexion beyond a comfortable range, and loading through the prosthetic joint components may be relatively well tolerated post-operatively compared to sensations experienced with loading through the osteoarthritic joint prior to surgery.

Study limitations include the relatively small sample size and the lack of kinetic and kinematic data which would have made it possible to analyze changes in gait with lower body positive pressure body weight support. Participants in this study were at least 6 weeks post-surgery and we do not know whether using a lower body positive pressure treadmill earlier in the rehabilitative process would result in more substantial changes in knee pain or ratings of perceived exertion with walking. Future research should continue to examine cardiovascular and metabolic responses, walking tolerance and pain ratings using lower body positive pressure treadmills for older adults with a variety of conditions affecting the musculoskeletal and neurological systems. It will also be important to determine whether walking changes (e.g., increased speed and/or tolerance) realized using body weight support can lead to improvements in daily function.

Conclusion

In summary, older adults with TKA demonstrated lower heart rate, systolic blood pressure, oxygen consumption and minute ventilation levels when walking under lower body positive pressure conditions. These responses are similar to those previously reported in younger individuals. Provision of body weight support allowed TKA patients to walk at faster speeds and/or to tolerate greater incline which may be important in the rehabilitation of these patients and others who would benefit from experiencing these types of walking challenges without increases in heart rate, blood pressure, or oxygen consumption.

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Conflict of interest The authors declare they have no conflict of interest.

References

American College of Sports Medicine (2013) ACSM's guidelines for exercise testing and prescription, 9th edn. Baltimore

Bennell KL, Hunt MA, Wrigley TV, Hunter DJ, McManus FJ, Hodges PW, Li L, Hinman RS (2010) Hip strengthening reduces symptoms but not knee load in people with medial knee osteoarthritis and varus malalignment: a randomised controlled trial. Osteoarthr Cartil 18:621–628

Boonstra MC, De Waal Malefijt MC, Verdonschot N (2008) How to quantify knee function after total knee arthroplasty? Knee 15:390–395

Borg G (1998) Borg's perceived exertion and pain scales. Champaign

Cheitlin MD (2003) Cardiovascular physiology-changes with aging. Am J Geriatr Cardiol 12:9–13

Cutuk A, Groppo ER, Quigley EJ, White KW, Pedowitz RA, Hargens AR (2006) Ambulation in simulated fractional gravity using lower body positive pressure: cardiovascular safety and gait analyses. J Appl Physiol 101:771–777

Decker LM, Cignetti F, Stergiou N (2012) Wearing a safety harness during treadmill walking influences lower extremity kinematics mainly through changes in ankle regularity and local stability. J Neuroeng Rehabil 9:8

Di MM, Vallero F, Tappero R, Cavanna A (2009) Rehabilitation after total hip arthroplasty: a systematic review of controlled trials on physical exercise programs. Eur J Phys Rehabil Med 45:303–317

Eastlack RK, Hargens AR, Groppo ER, Steinbach GC, White KK, Pedowitz RA (2005) Lower body positive-pressure exercise after knee surgery. Clin Orthop Relat Res 431:213–219

Gojanovic B, Cutti P, Shultz R, Matheson GO (2012) Maximal physiological parameters during partial body-weight support treadmill testing. Med Sci Sports Exerc 44:1935–1941

Grabowski AM (2010) Metabolic and biomechanical effects of velocity and weight support using a lower-body positive pressure device during walking. Arch Phys Med Rehabil 91:951–957

Hoffman MD, Donaghe HE (2011) Physiological responses to body weight-supported treadmill exercise in healthy adults. Arch Phys Med Rehabil 92:960–966

Irrgang JJ, Snyder-Mackler L, Wainner RS, Fu FH, Harner CD (1998) Development of a patient-reported measure of function of the knee. J Bone Joint Surg Am 80:1132–1145

Joffe D, Watkins M, Steiner L, Pfeifer BA (2002) Treadmill ambulation with partial body weight support for the treatment of low back and leg pain. J Orthop Sports Phys Ther 32:202–213

Johnson JA, McIlroy WE, Roy E, Papaioannou A, Thabane L, Giangregorio L (2013) Feasibility study of walking for exercise in individuals living in assisted living settings. J Geriatr Phys Ther 36:175–181

Kennedy DM, Stratford PW, Wessel J, Gollish JD, Penney D (2005) Assessing stability and change of four performance measures: a longitudinal study evaluating outcome following total hip and knee arthroplasty. BMC Musculoskelet Disord 6:3

Knikou M (2012) Plasticity of corticospinal neural control after locomotor training in human spinal cord injury. Neural Plast (serial on the internet). doi:10.1155/2012/254948

Kurz MJ, Corr B, Stuberg W, Volkman KG, Smith N (2011) Evaluation of lower body positive pressure supported treadmill training for children with cerebral palsy. Pediatr Phys Ther 23:232–239

Lewek MD (2011) The influence of body weight support on ankle mechanics during treadmill walking. J Biomech 44:128–133

Mangione KK, Axen K, Haas F (1996) Mechanical unweighting effects on treadmill exercise and pain in elderly people with osteoarthritis of the knee. Phys Ther 76:387–394

Millslagle D, Levy M, Matack N (2006) Kinematic assessment of treadmill running using different body-weight support harnesses. Percept Mot Skills 103:607–618

Miyai I, Fujimoto Y, Ueda Y, Yamamoto H, Nozaki S, Saito T, Kang J (2000) Treadmill training with body weight support: its effect on Parkinson's disease. Arch Phys Med Rehabil 81:849–852

Monahan KD (2007) Effect of aging on baroreflex function in humans. Am J Physiol Regul Integr Comp Physiol 293:R3–R12

Moore MN, Vandenakker-Albanese C, Hoffman MD (2010) Use of partial body-weight support for aggressive return to running after lumbar disk herniation: a case report. Arch Phys Med Rehabil 91:803–805

Moseley AM, Stark A, Cameron ID, Pollock A (2005) Treadmill training and body weight support for walking after stroke. Cochrane Database Syst Rev CD002840

Mutlu A, Krosschell K, Spira DG (2009) Treadmill training with partial body-weight support in children with cerebral palsy: a systematic review. Dev Med Child Neurol 51:268–275

Nishiyasu T, Nagashima K, Nadel ER, Mack GW (1998) Effects of posture on cardiovascular responses to lower body positive pressure at rest and during dynamic exercise. J Appl Physiol 85:160–167

Nishiyasu T, Hayashida S, Kitano A, Nagashima K, Ichinose M (2007) Effects of posture on peripheral vascular responses to lower body positive pressure. Am J Physiol Heart Circ Physiol 293:H670–H676

Patil S, Steklov N, Bugbee WD, Goldberg T, Colwell CW Jr, D'Lima DD (2013) Anti-gravity treadmills are effective in reducing knee forces. J Orthop Res 31:672–679

Phan-Ba R, Pace A, Calay P, Grodent P, Douchamps F, Hyde R, Hotermans C, Delvaux V, Hansen I, Moonen G, Belachew S (2011) Comparison of the timed 25-foot and the 100-meter walk as performance measures in multiple sclerosis. Neurorehabil Neural Repair 25:672–679

Raffalt PC, Hovgaard-Hansen L, Jensen BR (2013) Running on a lower-body positive pressure treadmill: VO_2max, respiratory response, and vertical ground reaction force. Res Q Exerc Sport 84:213–222

Rose MH, Lokkegaard A, Sonne-Holm S, Jensen BR (2013a) Effects of training and weight support on muscle activation in Parkinson's disease. J Electromyogr Kinesiol 23:1499–1504

Rose MH, Lokkegaard A, Sonne-Holm S, Jensen BR (2013b) Improved clinical status, quality of life, and walking capacity in Parkinson's disease after body weight-supported high-intensity locomotor training. Arch Phys Med Rehabil 94:687–692

Ruckstuhl H, Kho J, Weed M, Wilkinson MW, Hargens AR (2009) Comparing two devices of suspended treadmill walking by varying body unloading and Froude number. Gait Posture 30:446–451

Ruckstuhl H, Schlabs T, Rosales-Velderrain A, Hargens AR (2010) Oxygen consumption during walking and running under fractional weight bearing conditions. Aviat Space Environ Med 81:550–554

Shi X, Crandall CG, Raven PB (1993) Hemodynamic responses to graded lower body positive pressure. Am J Physiol 265: H69–H73

Takacs J, Anderson JE, Leiter JR, MacDonald PB, Peeler JD (2013) Lower body positive pressure: an emerging technology in the battle against knee osteoarthritis? Clin Interv Aging 8:983–991

Thomas EE, Stewart D, Mitchell S, Aiken K, Farina D, Macaluso A (2011) Comparison of neural activation and energy cost during treadmill walking with body weight unloading between frail and healthy older women. Gait Posture 33:356–360

Valentin-Gudiol M, Mattern-Baxter K, Girabent-Farres M, Bagur-Calafat C, Hadders-Algra M, Angulo-Barroso RM (2011) Treadmill interventions with partial body weight support in children under six years of age at risk of neuromotor delay. Cochrane Database Syst Rev CD009242

Williamson JW, Crandall CG, Potts JT, Raven PB (1994) Blood pressure responses to dynamic exercise with lower-body positive pressure. Med Sci Sports Exerc 26:701–708

Williamson JW, Raven PB, Whipp BJ (1996) Unaltered oxygen uptake kinetics at exercise onset with lower-body positive pressure in humans. Exp Physiol 81:695–705