

Effects of body weight support and gait velocity via antigravity treadmill on cardiovascular responses early after total knee arthroplasty

Bo Ryun Kim, MD, PhD^a, Sang Rim Kim, MD, PhD^{b,*}, Kwang Woo Nam, MD, PhD^b, So Young Lee, MD^a, Yong Geun Park, MD, PhD^b, Min Ji Suh, MD, PhD^a, Young Tae Jeon, MD^a

Abstract

To investigate the effects of body weight support (BWS) and gait velocity on cardiovascular responses during walking on an antigravity treadmill early after unilateral and bilateral total knee arthroplasty (TKA).

This study was a cross-sectional study design. Fifty patients (7 males and 43 females; average age, 72.0 ± 5.1 years) at 4 weeks after unilateral ($n=25$) and bilateral ($n=25$) primary TKA were enrolled in the study. Subjects walked on an antigravity treadmill at speeds of 2.5 km/hour and 3.5 km/hour with 3 levels (50%, 25%, and 0%) of BWS. Cardiovascular responses were monitored by measuring oxygen consumption (VO_2), heart rate (HR), systolic and diastolic blood pressure (SBP/DBP), the respiratory exchange ratio (RER), and rate pressure product (RPP). Borg rating of perceived exertion (RPE) and a visual analog scale (VAS) of knee pain were recorded immediately after each trial.

There were no significant differences in cardiovascular responses between the unilateral and bilateral TKA groups. In the repeated measures Analysis of Variance, VO_2 levels, HR, RPP, RPE, RER, and VAS were significantly increased in proportion to 3 levels (50%, 25%, and 0%) of BWS for unilateral and bilateral TKA groups, respectively. Meanwhile, SBP and DBP were unaffected by differences in BWS. At 3.5 km/hour, VO_2 , RPE, and RER values were statistically greater than those at 2.5 km/hour under the same BWS conditions.

We found that the reduction in the metabolic demand of activity, coupled with positive pressure on the lower extremities, reduced VO_2 and HR values as BWS increased.

Cardiovascular responses vary according to BWS and gait velocity during antigravity treadmill walking. BWS rather than gait velocity had the greatest effect on cardiovascular responses and knee pain.

Abbreviations: 10MWT = 10 m walk test, ASIS = anterior superior iliac spine, BMI = body mass index, BWS = body weight support, DBP = diastolic blood pressure, HR = heart rate, K-L = Kellgren–Lawrence, OA = osteoarthritis, RER = respiratory exchange ratio, ROM = range of motion, RPE = rating of perceived exertion, RPP = rate pressure product, SBP = systolic blood pressure, TKA = total knee arthroplasty, TUG = timed up and go test, VAS = visual analog scale, VO_2 = oxygen consumption.

Keywords: arthroplasty, cardiopulmonary exercise test, knee, osteoarthritis, rehabilitation

1. Introduction

Knee osteoarthritis (OA) is the leading cause of disability in older adults, in whom pain and swelling in the affected joint is often accompanied by a progressive decline in functional activity.^[1] Patients with end-stage knee OA are typically overweight and have lower limb muscle strength and lower exercise tolerance

than patients who do not have knee OA; this results in cardiovascular deconditioning.^[2–5]

Mean peak oxygen consumption (VO_2 peak) levels in those with end-stage knee OA typically range from 13.9 ± 3.3 to 14.4 ± 3.2 mL/kg/min.^[5,6] This is approximately 65% lower than those in age and sex-matched, nondisabled, sedentary (but otherwise

Editor: Justin Keogh.

The Jeju National University Hospital Ethics Committee(s) approved this study. All participants gave written informed consent before data collection began.

We certify that no party having a direct interest in the results of the research supporting this article has or will confer a benefit on us or on any organization with which we are associated.

This work was supported by a research grant from Jeju National University Hospital development fund in 2015.

The authors have no conflicts of interest to disclose.

^a Department of Rehabilitation Medicine, ^b Department of Orthopaedic Surgery, Regional Rheumatoid and Degenerative Arthritis Center, Jeju National University Hospital, Jeju National University School of Medicine, Jeju, South Korea.

* Correspondence: Sang Rim Kim, Department of Orthopaedic Surgery, Jeju National University School of Medicine, 102 Jejudaehakno, Jeju-si, Jeju-do, 63243, Republic of Korea (e-mail: kimsros2@gmail.com).

Copyright © 2020 the Author(s). Published by Wolters Kluwer Health, Inc.

This is an open access article distributed under the terms of the Creative Commons Attribution-Non Commercial License 4.0 (CCBY-NC), where it is permissible to download, share, remix, transform, and buildup the work provided it is properly cited. The work cannot be used commercially without permission from the journal.

How to cite this article: Kim BR, Kim SR, Nam KW, Lee SY, Park YG, Suh MJ, Jeon YT. Effects of body weight support and gait velocity via antigravity treadmill on cardiovascular responses early after total knee arthroplasty. *Medicine* 2020;99:14(e19586).

Received: 28 June 2019 / Received in final form: 3 February 2020 / Accepted: 18 February 2020

<http://dx.doi.org/10.1097/MD.00000000000019586>

healthy) individuals with no lower extremity arthritis (21.5 ± 3.9 mL/kg/min).^[6] Cardiovascular deconditioning not only reduces patient mobility, thereby impairing activities of daily living and reducing quality of life, but also worsens underlying cardiovascular and metabolic risk factors such as hypertension, obesity, diabetes, and dyslipidemia.^[6] Thus, patients scheduled for total knee arthroplasty (TKA) tend to show a higher prevalence of coronary heart disease.^[6] Smith et al^[7] reported that myocardial infarction is the most common cause of death within 30 days after elective hip and knee arthroplasty.

Patients with end-stage knee OA and undergoing TKA must perform intensive aerobic exercise, such as progressive gait training, to improve cardiovascular fitness early during the postoperative period. Early mobilization and rehabilitation after TKA reduces pain, fear, anxiety, and risk of postoperative venous thromboembolic disease.^[8] However, not all patients are capable of full weight-bearing activity at this time. Therefore, an antigravity treadmill is a useful device for early postoperative rehabilitation of patients post-TKA, particularly those with reduced physical strength and poor cardiovascular fitness.^[9,10] The antigravity treadmill comprises a treadmill enclosed within an airtight chamber. Air pressure applied to the lower body provides varying amounts of body weight support (BWS), thereby reducing the net ground reaction force and load on the knee joint during weight-bearing exercise. The antigravity treadmill does not affect gait kinematics or muscle activation, unlike other BWS training methods such as gait aids, therapeutic pools, and overhead suspension harnesses.^[9–13] In terms of gait speed, Gojanovic et al^[14] demonstrated antigravity treadmill training could provide equivalent maximal intensities for VO_2 and heart rate (HR) along with increases in peak gait velocity in athletes, and Webber et al^[9] confirmed that the BWS treadmill walking allowed patients post-TKA to walk faster and/or tolerate increased incline. The primary purpose of this study was to examine how cardiovascular responses to exercise on an antigravity treadmill under different BWS and gait velocity conditions affect during the early postoperative period. In addition, we wanted to know how to control BWS and gait velocity to maintain walking speed without worsening knee pain after TKA. Finally, we wondered whether the findings would be the same for patients with unilateral and bilateral TKA.

To the best of our knowledge, only 1 previous study has reported the cardiovascular responses of older adults with TKA both at rest and during submaximal exercise on an antigravity treadmill; however, that study enrolled only patients with unilateral TKA.^[9]

Therefore, this study was conducted to investigate the effects of BWS and gait velocity on cardiovascular responses during walking on an antigravity treadmill early after unilateral and bilateral TKA.

2. Subjects and methods

2.1. Experimental design

This was a cross-sectional study, and the allocation ratio of unilateral/bilateral TKA was 25 people per group, one to one.

2.2. Participants

This study enrolled 50 older people (7 males and 43 females; average age, 72.0 ± 5.1 years) who were diagnosed with end-stage primary OA of the knee and who underwent unilateral or

bilateral primary TKA at the Department of Orthopedic Surgery in OO National University Hospital between September 2015 and November 2016. Approximately 2 weeks after TKA, all patients were transferred to the Rehabilitation Department, where they took part in the study.

The inclusion criterion was the ability to walk without physical assistance either with or without an ambulatory aid. Patients with advanced congestive heart failure, peripheral arterial disease with claudication, unstable angina, and/or uncontrolled hypertension ($>190/110$ mm Hg), or previous neurological or orthopedic disease resulting in ambulatory deficits (e.g., orthopedic injury to a lower extremity that limited participation in exercise stress tests) were excluded.

All patients continued to take their usual medications throughout the screening period and antigravity treadmill walking tests. Each participant received information about the study and provided written informed consent. The study protocol was approved by the Institutional Review Board of OO National University Hospital.

2.3. Outcome measurements

An experienced physical therapist performed the following evaluation.

Assessment of baseline performance-based physical function was performed at the point of immediately after being transferred to Rehabilitation Department, approximately 2 weeks after surgery, and assessment of cardiovascular responses was performed approximately 4 weeks after surgery.

2.4. Assessment of baseline performance-based physical function

2.4.1. Timed up and go test. The timed up and go test (TUG) is used to evaluate dynamic balance. Each subject sat with their back against a chair (seat height, 44 cm; depth, 45 cm; width, 49 cm; arm rest height, 64 cm) placed at the end of a marked 3 m line. Patients were instructed to stand up on hearing the word “go,” walk at a comfortable speed until they passed the 3 m mark, turn around, walk back, and sit down again in the chair without any physical assistance. The test was timed. The TUG tool has acceptable concurrent validity for measuring dynamic balance.^[15]

2.4.2. Ten meter walk test. The 10 m walk test (10MWT) is a common measure used to assess walking speed. Extra distance was provided at the beginning and end of the timed 10 m walk to allow subjects enough space to accelerate/decelerate outside the data collection area; the aim was to reduce gait variability during the acceleration/deceleration phases. Walking speed was assessed at a pace selected by the participant; a wireless timer was used to record walking time. The 10MWT tool is the most valid clinical assessment of walking speed in healthy, older adults.^[16]

2.5. Testing procedure

The test was performed on an AlterG antigravity treadmill (Model M320; Alter G Inc, Fremont, CA). HR was monitored using a water-resistant chest-strap transmitter (Polar T34, Polar Electro, Inc, Kempele, Finland). Before stepping onto the treadmill, subjects put on specialized AlterG shorts, which were worn up to the level of the subject’s anterior superior iliac spine (ASIS). With the shorts on, the subject stepped into the opening of the AlterG treadmill. The metal frame that holds the air balloon

in place was raised to the level of the subject's ASIS. The shorts, which have a zipper lining, were then attached to the air balloon to create an air seal. Before the trial, a physical therapist adjusted the air pressure inside the chamber such that an appropriate lifting force was applied to each subject.

The first stage began with the subject positioned correctly in the AlterG. The subjects started to walk at 2.5 km/hour with 50% BWS. BWS was adjusted after each trial such that subjects were tested at 50%, 25%, and 0% BWS. The tests were then repeated at 3.5 km/hour under the same BWS conditions. Each trial was performed for 2 min, with at least 1 min between trials.

The test was terminated either at the request of the patient or if gait instability defined as marked unsteadiness and inconsistency from 1 stride to the next or cardiovascular decompensation became apparent (assessed in accordance with the guidelines of the American College of Sports Medicine).^[17]

2.6. Assessment of cardiovascular responses and knee pain

VO₂, HR, systolic and diastolic blood pressure (SBP/DBP), the respiratory exchange ratio (RER), and the rate pressure product (RPP) were measured. In addition, Borg rating of perceived exertion (RPE) scale and a visual analog scale (VAS) (for knee pain) were recorded immediately after each test.

VO₂ and the RER were determined by expired-gas analysis using the breath-by-breath method and a Cosmed K4b² portable telemetric system (Cosmed CPET, COSMED Inc, Pavana di Albano, Italy). The base harness was then arranged and the Cosmed K4b² system attached to the subject's torso. The K4b² has satisfactory reliability and validity.^[18] These values were calculated as the average of the values recorded during the last 30 seconds of the test. HR was measured as an average during the last 30 seconds of each test. SBP and DBP were measured using finometer (Finometer model-1, Finapres Medical Systems, Amsterdam, Netherlands) during the last 30 seconds of test. The RPP was also calculated ($[\text{HR} \times \text{SBP}]/100$) and expressed as the average of the values recorded during the last 30 seconds of the test.

The RPE is a quantitative measure of perceived exertion during physical activity, and ranges from 6 to 20, with 6 being rest and 20 being maximal effort.^[19] The VAS scale comprised a 10-cm-long horizontal line ranging from no pain to worst pain possible. Facial expressions were placed above the line to express pain visually. The VAS system ranged from 0 (no pain) to 10 (worst pain possible).^[20] All patients used this scale and were asked to mark the line at a point that matched their pain level.

2.7. Statistical analysis

All statistical analyses were performed using SPSS for windows version 18 (IBM-SPSS, Inc, Chicago, IL). All variables were analyzed using descriptive statistics. In the demographics, disease-related characteristics, and baseline performance-based physical function, Student *t* test was used to determine significance differences for continuous variables between patients with unilateral TKA and bilateral TKA, while Fisher exact test was used for categorical variables. In addition, Student *t* test was used to compare cardiovascular responses and knee pain between patients with unilateral TKA and bilateral TKA. Two-way repeated measures Analysis of Variance and Turkey's post-hoc tests were conducted to compare cardiovascular responses and

knee pain at different levels of BWS and different gait velocities within each TKA group. Then, multiple linear regressions were used to determine the combined effects of BWS and gait velocity on VO₂ within each TKA group. *P* < .05 was considered statistically significant.

3. Results

3.1. Flow of participants through the trial

A total of 102 participants that were admitted between September 2015 and November 2016 were screened for inclusion. Of the excluded patients, 38 patients had a history of previous orthopedic injury and 11 patients had advanced congestive heart failure, peripheral arterial disease with claudication, unstable angina, and uncontrolled hypertension. The remaining 3 patients who had a history of neurological disease such as stroke and myelopathy were excluded. The remaining 50 patients were eligible, and agreed to participate.

3.2. Demographics, disease-related characteristics, and physical function

Baseline demographics, disease-related characteristics, and average baseline performance-based physical function data are presented in Table 1. The average body mass index was 26.0 ± 3.5 kg/m². The average TUG and 10MWT values were 10.5 ± 1.9 seconds and 11.3 ± 2.5 seconds, respectively. There were no significant differences (except the number of patients with osteoporosis) between the unilateral TKA and bilateral TKA groups.

3.3. Evaluation of cardiovascular responses and pain

The average VO₂, HR, SBP, DBP, RER, RPP, RPE, and VAS values under the 3 different BWS conditions (50%, 25%, 0% BWS) and 2 gait velocity conditions (2.5 km/h and 3.5 km/h) are presented in Table 2. The student *t* test was used to compare cardiovascular responses and knee pain between patients with unilateral TKA and bilateral TKA. The average VO₂ values ranged from 10.8 ± 2.0 to 16.5 ± 3.4 mL/kg/min, and there were no significant differences between the unilateral TKA and bilateral TKA groups.

3.4. Main and interaction effects of BWS and gait velocity within unilateral TKA group

There were main effects of BWS on VO₂ ($F[\text{df}=2]=117.442$, $P < .001$), HR ($F[\text{df}=2]=113.156$, $P < .001$), RPP ($F[\text{df}=2]=40.877$, $P < .001$), RPE ($F[\text{df}=2]=40.877$, $P < .001$), RER ($F[\text{df}=2]=12.201$, $P < .001$), VAS ($F[\text{df}=2]=27.390$, $P < .001$), indicating that VO₂, HR, RER, RPP, RPE, and VAS increased as BWS decreased. Post-hoc analysis revealed a significant difference under all conditions. There were no significant main effects of BWS on SBP and DBP.

There were main effects of gait velocity on VO₂ ($F[\text{df}=1]=5.851$, $P = .019$), RPE ($F[\text{df}=1]=13.134$, $P = .001$), RER ($F[\text{df}=1]=11.751$, $P = .001$), showing that VO₂, RPE, RER increased with each increase in gait velocity. Post-hoc analysis revealed a significant difference under all conditions. There were no significant main effects of gait velocity on HR, SBP, DBP, RPP, and VAS. A significant interaction between BWS and gait velocity was found on RPP ($F[\text{df}=2]=3.690$, $P = .032$), indicating that the association of BWS and RPP may vary across conditions of gait

Table 1
Baseline demographics, disease-related characteristics, and baseline performance-based physical function (N=50).

Variable	Total (n=50)	Unilateral (n=25)	Bilateral (n=25)	P
Age (yrs)	72.0±5.1	72.6±4.9	71±5.4	.38
Sex, males/females	7 (14.0)/43 (86.0)	2 (8.0)/23 (92.0)	5 (10.0)/20 (80.0)	.42
Height (cm)	153.5±6.4	153.7±6.65	153.3±6.2	.83
Weight (kg)	61.2±9.5	61.8±9.6	60.5±9.5	.64
BMI (kg/m ²)	26.0±3.5	26.1±3.5	25.9±3.6	.87
K-L grades				.17
Grade 3	11 (22.0)	8 (32.0)	3 (12.0)/5 (20.0)	
Grade 4	39 (78.0)	17 (68.0)	22 (88.0)/20 (80.0)	
Lesion side				
Left	15 (60.0)	15 (60.0)		
Right	10 (40.0)	10 (40.0)		
Both	25 (100)		25 (100)	
Comorbidities				
Hypertension	27 (54.0)	15 (60.0)	12 (48.0)	.57
Diabetes mellitus	11 (22.0)	7 (28.0)	4 (16.0)	.50
Spine disease	8 (16.0)	3 (12.0)	5 (20.0)	.70
Osteoporosis	18 (36.0)	5 (20.0)	13 (52.0)	.04
ROM (degrees)				
Knee flexion	114.0±11.1	112.2±9.4	115.7±12.8	.46
Knee extension	-4.2±4.5	-6.7±5.7	-1.6±3.3	.18
TUG (s)	10.5±1.9	10.1±1.7	10.9±2.0	.16
10MWT (s)	11.3±2.5	11.5±2.7	11.1±2.3	.64

Values represent mean ± standard deviation or number (%) of cases.

10MWT=10m walk test, BMI=body mass index, K-L=Kellgren–Lawrence, ROM=range of motion, TUG=timed up and go.

velocity. There were no significant interactions between BWS and gait velocity on VO₂, HR, SBP, DBP, RER RPE, and VAS (Table 3).

In addition, multiple linear regression analysis was performed to define VO₂ as a function of gait velocity and fraction of BWS under each condition. Based on BWS and gait velocity settings, the equation was VO₂ = 1.5 v + 0.1 BW + 3.1 (adjusted R₂ = 0.39).

3.5. Main and interaction effects of BWS and gait velocity within bilateral TKA group

There were main effects of BWS on VO₂ (F[df=2]=82.695, *P* < .001), HR (F[df=2]=82.731, *P* < .001), RPP (F[df=2]=30.997, *P* < .001), RPE (F[df=2]=53.597, *P* < .001), RER (F[df=2]=16.961, *P* < .001), VAS (F[df=2]=24.821, *P* < .001), indicating that VO₂, HR, RER, RPP, RPE, and VAS increased as BWS decreased. Post-hoc analysis revealed that all other conditions except comparison of RER values between 50% of BWS condition and 25% of BWS condition under a speed of 2.5 km/hour and a speed of 3.5 km/hour were statistically significant. There were no significant main effects of BWS on SBP and DBP.

There were main effects of gait velocity on VO₂ (F[df=1]=4.113, *P* = .049), RPE (F[df=1]=9.290, *P* = .004), RER (F[df=1]=6.572, *P* = .014), showing that VO₂, RPE, RER increased with each increase in gait velocity. Post-hoc analysis revealed that all other conditions except comparison of RER values between a speed of 2.5 km/hour and a speed of 3.5 km/hour under 0% of BWS condition were statistically significant. There were no significant main effects of gait velocity on HR, SBP, DBP, RPP, and VAS. A significant interaction between BWS and gait velocity was found on HR (F[df=2]=4.260, *P* = .022), RPP (F[df=2]=4.658, *P* = .016), indicating that the association of BWS and HR, RPP may vary across conditions of gait velocity. There were no significant interactions between BWS and gait velocity on VO₂, SBP, DBP, RER RPE, and VAS (Table 4).

As above, multiple linear regression analysis was performed to define VO₂ as a function of gait speed and BWS level. Based on BWS and gait velocity settings, the equation was VO₂ = 1.5 v + 0.1 BW + 3.1 (adjusted R₂ = 0.34).

4. Discussion

Here, we examined the cardiovascular responses of patients post-TKA walking on an antigravity treadmill under different BWS conditions and velocities. We then compared the results for unilateral TKA with those for bilateral TKA and tried to assess whether the values obtained can be used to determine appropriate exercise levels postsurgery.

The primary question was as follows: How do BWS and gait velocity affect cardiovascular responses during the early postoperative period after TKA? We found that VO₂, HR, RPP, RPE, RER, and the VAS varied significantly under different BWS conditions (50%, 25%, 0%), and that, under the same BWS conditions, VO₂, RPE, and RER values were statistically greater at 3.5 km/hour than at 2.5 km/hour.

Exerting positive pressure on the lower body to reduce the net ground reaction force and allow ambulation under different BWS conditions reduces the metabolic cost of walking and alters cardiovascular responses.^[9] Regulation of VO₂ depends on both central (i.e., cardiac output [expressed mathematically as HR × stroke volume]) and peripheral (i.e., differences in arteriovenous oxygen levels) mechanisms.^[15] Exerting pressure around the lower extremities during antigravity treadmill walking likely increases venous return and mean arterial pressure, with a subsequent reflexive reduction in HR due to baroreceptor stimulation in the arterial system; this will reduce demand on the heart as a central mechanism. BWS under antigravity treadmill reduces the ground reaction force on the lower extremities, decrease muscle contraction, and reduce oxygen

Table 2
Evaluation of cardiorespiratory responses.

Variable	Total (n=50)	Unilateral (n=35)	Bilateral (n=25)	P
VO₂ (mL/kg/min)				
2.5 km/h, 50% BWS	10.8±2.1	10.8±2.0	10.9±2.0	.94
2.5 km/h, 25% BWS	12.7±2.1	12.6±2.1	12.8±2.1	.95
2.5 km/h, 0% BWS	14.8±2.3	14.8±2.0	14.9±2.6	.98
3.5 km/h, 50% BWS	12.3±2.4	12.3±2.4	12.4±2.4	.95
3.5 km/h, 25% BWS	14.0±2.5	14.0±2.5	14.1±2.4	.93
3.5 km/h, 0% BWS	16.4±3.0	16.3±2.6	16.5±3.4	.96
HR (beats/min)				
2.5 km/h, 50% BWS	92.3±10.6	91.0±10.9	93.6±10.4	.38
2.5 km/h, 25% BWS	98.0±11.7	96.9±11.3	99.0±12.3	.57
2.5 km/h, 0% BWS	103.8±11.4	103.2±11.7	104.3±11.4	.74
3.5 km/h, 50% BWS	99.7±12.4	99.2±11.9	101.2±12.9	.43
3.5 km/h, 25% BWS	103.6±12.6	102.2±12.2	105.1±13.0	.46
3.5 km/h, 0% BWS	110.2±14.3	110.1±15.1	110.4±13.9	.99
SBP (mm Hg)				
2.5 km/h, 50% BWS	162.6±23.6	160.9±20.0	164.4±27.1	.43
2.5 km/h, 25% BWS	162.9±25.7	159.2±21.4	166.6±29.3	.23
2.5 km/h, 0% BWS	164.2±29.5	161.0±22.3	167.4±35.4	.35
3.5 km/h, 50% BWS	165.6±23.5	161.0±22.3	169.3±28.0	.21
3.5 km/h, 25% BWS	162.1±25.6	155.6±20.8	168.5±28.7	.06
3.5 km/h, 0% BWS	162.4±25.0	160.8±21.2	164.1±28.6	.55
DBP (mm Hg)				
2.5 km/h, 50% BWS	82.1±10.0	81.6±8.4	82.6±11.5	.67
2.5 km/h, 25% BWS	82.5±11.3	81.0±8.9	84.2±13.2	.33
2.5 km/h, 0% BWS	84.1±13.7	82.1±8.6	86.2±17.4	.31
3.5 km/h, 50% BWS	84.1±10.1	82.9±7.1	85.3±12.5	.43
3.5 km/h, 25% BWS	83.6±12.9	82.1±8.6	86.0±15.8	.20
3.5 km/h, 0% BWS	83.6±11.4	82.7±8.4	84.5±13.9	.64
RER				
2.5 km/h, 50% BWS	0.81±0.06	0.80±0.05	0.81±0.07	.37
2.5 km/h, 25% BWS	0.81±0.06	0.81±0.05	0.81±0.06	.61
2.5 km/h, 0% BWS	0.84±0.05	0.84±0.05	0.85±0.06	.68
3.5 km/h, 50% BWS	0.87±0.08	0.86±0.07	0.89±0.09	.14
3.5 km/h, 25% BWS	0.85±0.06	0.85±0.05	0.86±0.07	.58
3.5 km/h, 0% BWS	0.88±0.09	0.87±0.05	0.89±0.12	.51
RPP				
2.5 km/h, 50% BWS	14995.7±2750.1	14584.7±2281.7	15406.7±3143.8	.21
2.5 km/h, 25% BWS	15777.1±3056.3	15395.2±2560.7	16159.1±3494.3	.32
2.5 km/h, 0% BWS	17042.6±3440.1	16639.0±2894.6	17446.3±3929.7	.33
3.5 km/h, 50% BWS	16531.7±3281.8	15868.5±2392.7	17194.8±3917.7	.14
3.5 km/h, 25% BWS	16844.4±3209.8	16015.9±2725.4	17672.8±3489.5	.60
3.5 km/h, 0% BWS	17852.7±3680.4	17687.6±3330.5	18017.8±4062.8	.72
RPE (points)				
2.5 km/h, 50% BWS	9.6±1.6	9.4±1.7	9.9±1.5	.57
2.5 km/h, 25% BWS	11.2±1.8	11.1±1.7	11.3±2.0	.67
2.5 km/h, 0% BWS	12.9±1.9	13.1±1.7	12.7±2.1	.47
3.5 km/h, 50% BWS	11.3±2.1	11.7±2.3	10.9±1.8	.30
3.5 km/h, 25% BWS	12.7±2.1	13.0±2.3	12.4±1.9	.22
3.5 km/h, 0% BWS	14.4±2.3	14.4±2.1	14.5±2.4	.95
VAS				
2.5 km/h, 50% BWS	0.9±1.3	1.0±1.3	0.9±1.4	.84
2.5 km/h, 25% BWS	1.6±1.8	1.9±2.1	1.4±1.5	.31
2.5 km/h, 0% BWS	2.6±2.3	3.2±2.6	2.0±1.8	.05
3.5 km/h, 50% BWS	1.8±2.4	2.1±2.9	1.5±1.8	.33
3.5 km/h, 25% BWS	2.5±2.5	2.9±2.7	2.1±2.2	.22
3.5 km/h, 0% BWS	3.2±2.8	3.7±3.1	2.7±2.6	.20

Values represent mean ± standard deviation.

BWS = body weight support, DBP = diastolic blood pressure, HR = heart rate, RER = respiratory exchange ratio, RPE = rating of perceived exertion, RPP = rate pressure product, SBP = systolic blood pressure, VAS = visual analog scale, VO₂ = oxygen consumption.

Table 3
Cardiorespiratory responses and knee pain at different levels of body weight support and gait velocity during antigravity treadmill walking: unilateral total knee arthroplasty group.

Variable/condition	50% BWS	25% BWS	0% BWS
VO ₂ (mL/kg/min)			
2.5 km/h	10.8±2.0	12.6±2.1*	14.8±2.0*
3.5 km/h	12.3±2.4†	14.0±2.5*†	16.3±2.6*†
HR (beats/min)			
2.5 km/h	91.0±10.9	96.9±11.3*	103.2±11.7*
3.5 km/h	99.2±11.9	102.2±12.2*	110.1±15.1*
SBP (mm Hg)			
2.5 km/h	160.9±20.0	159.2±21.4	161.0±22.3
3.5 km/h	161.9±17.7	155.6±20.8	160.8±21.2
DBP (mm Hg)			
2.5 km/h	81.6±8.4	81.0±8.9	82.1±8.6
3.5 km/h	82.9±7.1	82.1±8.6	82.7±8.4
RER			
2.5 km/h	0.80±0.05	0.81±0.05*	0.84±0.05*
3.5 km/h	0.86±0.07†	0.85±0.05*†	0.87±0.05*†
RPP			
2.5 km/h	14585±2282	15395±2561*	16639±2895*
3.5 km/h	15869±2393	16016±2725*	17688±3331*
RPE (points)			
2.5 km/h	9.4±1.7	11.1±1.7*	13.1±1.7*
3.5 km/h	11.7±2.3†	13.0±2.3*†	14.4±2.1*†
VAS			
2.5 km/h	1.0±1.3	1.9±2.1*	3.2±2.6*
3.5 km/h	2.1±2.9	2.9±2.7*	3.7±3.1*

Values represent mean±standard deviation.

BWS = body weight support, DBP=diastolic blood pressure, HR=heart rate, RER=respiratory exchange ratio, RPE=rating of perceived exertion, RPP=rate pressure product, SBP=systolic blood pressure, VAS=visual analog scale, VO₂=oxygen consumption.

* Significant difference from the 50% BWS condition at the same velocity ($P < .05$).

† Significant difference from the 2.5 km/h at the same fraction of BWS condition ($P < .05$).

extraction in the periphery; this will reduce demand on the heart as a peripheral mechanism.^[9,11,12] However, our results showed that SBP and DBP were not affected by BWS conditions. Webber et al^[9] found that SBP and DBP were not affected by BWS conditions, and Cutuk et al^[11] reported SBP and DBP, although trending upward, did not significantly increase in the treadmill ambulating subjects exposed to 20 to 50 mm Hg of lower body positive pressure. Considering these results, the reduced metabolic demand to heart during antigravity treadmill walking would be likely more attributable to a peripheral mechanism rather than a central mechanism. The decreased HR at increasing levels of BWS could be also likely less demanding on the heart due to the lighter workload during antigravity treadmill. In addition, these findings could benefit older adults with not only TKA but also a wide variety of musculoskeletal conditions because majority of older adults typically have higher resting blood pressures and decreased reactivity of baroreceptors compared with younger people.^[21,22]

Here, we found that the reduction in the metabolic demand of activity, coupled with positive pressure on the lower extremities, reduced VO₂ and HR values as BWS increased. We found that increasing BWS by 25% reduced VO₂ by 12.1% to 14.8% and HR by 3.4% to 6.0%. Whereas the previous study reporting cardiovascular response in older adults after TKA on a positive pressure treadmill showed that increasing BWS by 40% reduced VO₂ by 17.7% to 23.1% and HR by 7.8% to 12.4%.^[9] The differences between the present and previous studies appear to be due to factors such as the age, functional status, underlying

Table 4
Cardiorespiratory responses and knee pain at different levels of body weight support and gait velocity during antigravity treadmill walking: bilateral total knee arthroplasty group.

Variable/condition	50% BWS	25% BWS	0% BWS
VO ₂ (mL/kg/min)			
2.5 km/h	10.9±2.0	12.8±2.1*	14.9±2.6*
3.5 km/h	12.4±2.4†	14.1±2.4*†	16.5±3.4*†
HR (beats/min)			
2.5 km/h	93.6±10.4	99.0±12.3*	104.3±11.4*
3.5 km/h	101.2±12.9	105.1±13.0*	110.4±13.9*
SBP (mm Hg)			
2.5 km/h	164.4±27.1	166.6±29.3	167.4±35.4
3.5 km/h	169.3±28.0	168.5±28.7	164.1±28.6
DBP (mm Hg)			
2.5 km/h	82.6±11.5	84.2±13.2	86.2±17.4
3.5 km/h	85.3±12.5	86.0±15.8	84.5±13.9
RER			
2.5 km/h	0.81±0.07	0.81±0.06	0.85±0.06*
3.5 km/h	0.89±0.09†	0.86±0.07†	0.89±0.12*
RPP			
2.5 km/h	15406±3144	16159±3494*	17446±3929*
3.5 km/h	17195±3917	17672±3490*	18018±4063*
RPE (points)			
2.5 km/h	9.9±1.5	11.3±2.0*	12.7±2.1*
3.5 km/h	10.9±1.8†	12.4±1.9*†	14.5±2.4*†
VAS			
2.5 km/h	0.9±1.4	1.4±1.5*	2.0±1.8*
3.5 km/h	1.5±1.8	2.1±2.2*	2.7±2.6*

Values represent mean±standard deviation.

BWS = body weight support, DBP=diastolic blood pressure, HR=heart rate, RER=respiratory exchange ratio, RPE=rating of perceived exertion, RPP=rate pressure product, SBP=systolic blood pressure, VAS=visual analog scale, VO₂=oxygen consumption.

* Significant difference from the 50% BWS condition at the same velocity ($P < .05$).

† Significant difference from the 2.5 km/h at the same fraction of BWS condition ($P < .05$).

disease, postoperative duration, and workload, including walking speed.

The RPP value is calculated as HR × SBP. We also found that the RPP value fell significantly (due to a decrease in HR) as BWS increased, as did the RPE and RER values.

The RPE scale has been validated against physiologic measures such as VO₂^[19]; thus we would expect a significant correlation between reduced RPE values and reduced VO₂ due to the reduced aerobic demand and lower body positive pressure. In addition, we found that knee pain decreased significantly as BWS increased; this is in contrast to the findings of previous studies of patients after TKA or meniscectomy, which report little change in knee pain, regardless of the amount of BWS provided by the antigravity treadmill.^[9,12] However, the previous study focused on patients who had undergone TKA about 8 weeks before testing. Using an antigravity treadmill earlier in the postoperative period may result in more marked differences in pain ratings under conditions of BWS. Therefore, the results of the previous study should be interpreted differently from those of our own because we evaluated patients at about 4 weeks after surgery. On the other hand, when we compared walking speeds of 2.5 km/hour and 3.5 km/hour under the same BWS conditions, we found that only VO₂, RPE, and RER values were significantly greater at the higher speed in both groups.

The results suggest that BWS has a greater effect on cardiovascular responses and knee pain than gait velocity, although it should be noted that the difference in the latter was only 1 km/hour. When we performed multiple linear regression

analysis to define VO_2 as a function of gait speed and BWS under each set of conditions, the following equation emerged: $VO_2 = 1.5 v + 0.1 BWS + 3.1$. That is, VO_2 can be derived from various combinations of BWS and gait velocity, and the BWS of 15% and the speed of 1 km/hour are similar to the VO_2 value.

These results have important clinical implications because they provide clues as to how BWS and gait velocity conditions on the antigravity treadmill can be adjusted during the early postoperative period to provide exercise at an appropriate intensity without worsening knee pain. The intensity of cardiorespiratory exercise can be measured by assessing RPE.^[15] The results on the RPE scale ranged from 10 to 14 points under controlled BWS and gait velocity conditions; this means that patients perceived the test as “fairly light” to “somewhat hard.” Aerobic exercise at moderate intensity usually results in a RPE score of 12 to 14; therefore, the exercise intensity used in the present study seems appropriate. In addition, there was no significant main effect of gait velocity on VAS while main effect of BWS on VAS was significant. Considering these findings, when gait training on an antigravity treadmill during the early postoperative period, it is preferable to first increase gait velocity from 2.5 km/hour to 3.5 km/hour while at the maximum BWS level (50% BWS), and then to gradually reduce BWS as postoperative knee pain allows.

Here, we set the gait velocities at 2.5 km/hour and 3.5 km/hour because 2.5 km/hour was average self-selected gait speed in community-dwelling older adults suggested by Singh et al^[23] and 3.5 km/hour was closest to the average gait speed (0.9 m/s) measured in the 10MWT suggested by our study. Gait velocity is a key factor in diagnosing sarcopenia, and has the potential to predict future functional decline and fall risk.^[24–26] Furthermore, a decline in gait velocity is associated with several health-related factors, including disability, hospitalization, loss of independence, and mortality.^[15,27–30] Therefore, provision of BWS during the early postoperative period allows a patient to undertake appropriate levels of aerobic exercise at a faster gait velocity. Although gait aids such as crutches, walkers, and canes support body weight, they are limited because a patient cannot maintain a sufficiently high gait velocity over an appropriate period of time during exercise, and use of gait aids markedly alter joint and gait mechanics.^[12,31]

Finally, we found that the cardiovascular responses of the unilateral TKA group were similar to those of the bilateral TKA group; the only difference was the significance of some values after post-hoc analysis. There were no significant differences between the 2 groups in terms of performance-based physical function.

This study has several limitations. First, each group contained a small number of patients. Second, we used 50%, 25%, and 0% BWS; however, a previous study^[32] that examined unloading on an antigravity treadmill suggests that the device is most accurate in the 10% to 30% range of BWS; differences at the higher (0% BWS) and lower (70%–80% BWS) end of the spectrum were relatively large (>5%). Of note, under the “0% BWS” condition, the antigravity treadmill actually provides about 7% BWS. These limitations should be taken into consideration when interpreting cardiovascular responses, especially those recorded at 0% BWS. In addition, these limitations should be also taken into consideration when using other BWS systems. Third, the same order of BWS was used for each participant; this could have affected their pain scores. Finally, our patients received inpatient physical therapy for the 4 weeks leading up to the testing, and this

extensive rehabilitation might influence on the cardiovascular responses. Thus, these findings could not be generalized to patients who have not received rehabilitation at the same postsurgical time point.

5. Conclusion

Here, we demonstrate that cardiovascular responses are affected by a combination of BWS and gait velocity during training on an antigravity treadmill. Also, the level of knee pain experienced during exercise was influenced more by the level of BWS than by gait velocity. Therefore, when attempting to improve aerobic conditioning of patients after TKA (using an antigravity treadmill and/or walking aids), BWS and gait velocity should be considered carefully and set appropriately.

Author contributions

Conceptualization: Bo Ryun Kim, Sang Rim Kim.

Data curation: Bo Ryun Kim, Kwang Woo Nam, Yong Geun Park.

Investigation: Sang Rim Kim.

Methodology: Bo Ryun Kim, Kwang Woo Nam, So Young Lee, Young Tae Jeon.

Supervision: Sang Rim Kim, So Young Lee.

Writing – original draft: Bo Ryun Kim, Min Ji Suh, Young Tae Jeon.

References

- Peat G, McCarney R, Croft P. Knee pain and osteoarthritis in older adults: a review of community burden and current use of primary health care. *Ann Rheum Dis* 2001;60:91–7.
- Beals C, Lampman R, Banwell B, et al. Measurement of exercise tolerance in patients with rheumatoid arthritis and osteoarthritis. *J Rheumatol* 1985;12:458–61.
- Ike RW, Lampman RM, Castor CW, et al. Arthritis and aerobic exercise: a review. *Phys Sportsmed* 1989;17:128–38.
- Nordesjö L-O, Nordgren B, Wigren A, et al. Isometric strength and endurance in patients with severe rheumatoid arthritis or osteoarthritis in the knee joints. *Scand J Rheumatol* 1983;12:152–6.
- Philbin EF, Groff GD, Ries MD, Miller TE. Cardiovascular fitness and health in patients with end-stage osteoarthritis. *Arthritis Rheumatol* 1995;38:799–805.
- Ries MD, Philbin EF, Groff GD. Relationship between severity of gonarthrosis and cardiovascular fitness. *Clin Orthop Relat Res* 1995;313:169–76.
- Smith E, Maru M, Siegmeth A. Thirty-Day mortality after elective hip and knee arthroplasty. *Surgeon* 2015;13:5–8.
- Pearse EO, Caldwell BF, Lockwood RJ, Hollard J. Early mobilisation after conventional knee replacement may reduce the risk of postoperative venous thromboembolism. *J Bone Joint Surg Br* 2007;89:316–22.
- Webber SC, Horvey KJ, Pikaluk MT, Butcher SJ. Cardiovascular responses in older adults with total knee arthroplasty at rest and with exercise on a positive pressure treadmill. *Eur J Appl Physiol* 2014;114:653–62.
- Bugbee W, Pulido P, Goldberg T, D’Lima DD. Use of an anti-gravity treadmill for early postoperative rehabilitation after total knee replacement: a pilot study to determine safety and feasibility. *Am J Orthop (Belle Mead NJ)* 2016;45:E167–73.
- Cutuk A, Groppo ER, Quigley EJ, et al. Ambulation in simulated fractional gravity using lower body positive pressure: cardiovascular safety and gait analyses. *J Appl Physiol* (1985) 2006;101:771–7.
- Eastlack RK, Hargens AR, Groppo ER, et al. Lower body positive-pressure exercise after knee surgery. *Clin Orthop Relat Res* 2005;431:213–9.
- Grabowski AM. Metabolic and biomechanical effects of velocity and weight support using a lower-body positive pressure device during walking. *Arch Phys Med Rehabil* 2010;91:951–7.

- [14] Gojanovic B, Cutti P, Shultz R, Matheson GO. Maximal physiological parameters during partial body-weight support treadmill testing. *Med Sci Sports Exerc* 2012;44:1935–41.
- [15] Podsiadlo D, Richardson S. The timed “Up & Go”: a test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc* 1991;39:142–8.
- [16] Peters DM, Fritz SL, Krotish DE. Assessing the reliability and validity of a shorter walk test compared with the 10-meter walk test for measurements of gait speed in healthy, older adults. *J Geriatr Phys Ther* 2013;36:24–30.
- [17] Medicine ACoS. *ACSM’s guidelines for exercise testing and prescription*: Lippincott Williams & Wilkins; 2013
- [18] Duffield R, Dawson B, Pinnington HC, et al. Accuracy and reliability of a Cosmed K4b2 portable gas analysis system. *J Sci Med Sport* 2004;7:11–22.
- [19] Borg GA, Noble BJ. Perceived exertion. *Exerc Sport Sci Rev* 1974;2:131–54.
- [20] Carlsson AM. Assessment of chronic pain. I. Aspects of the reliability and validity of the visual analogue scale. *Pain* 1983;16:87–101.
- [21] Cheitlin MD. Cardiovascular physiology-changes with aging. *Am J Geriatr Cardiol* 2003;12:9–13.
- [22] Monahan KD. Effect of aging on baroreflex function in humans. *Am J Physiol Regul Integr Comp Physiol* 2007;293:R3–12.
- [23] Singh H, Sanders O, Waller SM, et al. Relationship between head-turn gait speed and lateral balance function in community-dwelling older adults. *Arch Phy Med Rehabil* 2017;98:1955–61.
- [24] Montero-Odasso M, Schapira M, Soriano ER, et al. Gait velocity as a single predictor of adverse events in healthy seniors aged 75 years and older. *J Gerontol A Biol Sci Med Sci* 2005;60:1304–9.
- [25] De Rekeneire N, Visser M, Peila R, et al. Is a fall just a fall: correlates of falling in healthy older persons. The Health, Aging and Body Composition Study. *J Am Geriatr Soc* 2003;51:841–6.
- [26] Chen LK, Liu LK, Woo J, et al. Sarcopenia in Asia: consensus report of the Asian Working Group for Sarcopenia. *J Am Med Dir Assoc* 2014;15:95–101.
- [27] Studenski S, Perera S, Wallace D, et al. Physical performance measures in the clinical setting. *J Am Geriatr Soc* 2003;51:314–22.
- [28] Hardy SE, Perera S, Roumani YF, et al. Improvement in usual gait speed predicts better survival in older adults. *J Am Geriatr Soc* 2007;55:1727–34.
- [29] Kuo H-K, Leveille SG, Yen C-J, et al. Exploring how peak leg power and usual gait speed are linked to late-life disability: data from the National Health and Nutrition Examination Survey (NHANES), 1999–2002. *Am J Phys Med Rehabil* 2006;85:650–8.
- [30] Penninx BW, Ferrucci L, Leveille SG, et al. Lower extremity performance in nondisabled older persons as a predictor of subsequent hospitalization. *J Gerontol A Biol Sci Med Sci* 2000;55:M691–7.
- [31] Toots A, Littbrand H, Holmberg H, et al. Walking aids moderate exercise effects on gait speed in people with dementia: a randomized controlled trial. *J Am Med Dir Assoc* 2017;18:227–33.
- [32] McNeill DK, de Heer HD, Bounds RG, Coast JR. Accuracy of unloading with the anti-gravity treadmill. *J Strength Cond Res* 2015;29:863–8.