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Effects of body weight support and pedal stance width on joint loading during pinnacle trainer exercise

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ABSTRACT

Background: A pinnacle trainer is a stair climber that has a biplane exercise trajectory and an adjustable pedal stance width (PSW). A pinnacle trainer integrated with a body weight support (BWS) system can help overweight individuals or individuals with poor balance exercise safely by reducing excessive or improper joint loads, preventing training-related injuries. However, few studies have investigated the biomechanical features of the lower extremities during pinnacle trainer exercise with and without partial BWS for various PSWs.
Research question: We aimed to investigate the effects of partial BWS and PSW on the joint loading of the lower extremities during stepping on a pinnacle trainer.
Methods: Seventeen healthy adults exercised on the pinnacle trainer with or without BWS using various PSWs. The joint resultant forces and joint moments of the lower extremities were calculated according to the kinematic and kinetic data measured via a motion capture system and force transducers on the pedals, respectively.
Results: The joint resultant forces and joint moments of the lower extremities significantly decreased with increasing percentage of BWS. The internal knee adduction moment and internal hip abduction moment significantly increased with increasing PSW. For every kilogram of BWS, the joint loading of the lower extremities decreased by approximately 1% of the joint resultant forces of body weight during exercise with the pinnacle trainer.
Significance: Exercise on the pinnacle trainer with partial BWS significantly reduced joint loading. Exercise with a wider pedal stance may be helpful for knee osteoarthritis rehabilitation as it produces greater internal hip abduction and internal knee adduction moments.

1. Introduction

Exercise with pedal-type equipment has become popular due to the reduced external impact forces and consequent joint loading during exercise compared to those for level walking [1]. Exercise on regular fitness equipment is relatively easy for healthy individuals, but might be unsuitable for certain people, e.g., individuals with neurological or orthopedic problems or obesity, due to their fragility or biomechanical considerations. Hence, it is important to develop systems such as a body weight support (BWS) system to provide a safe exercise environment for individuals with poor balance ability or obesity, which increase joint loadings during exercise. The increased loadings on joints and nearby muscles may cause early fatigue during exercise, which may limit exercise duration [1]. Muscular fatigue may induce abnormal gait patterns and result in musculoskeletal injuries. Moreover, increased joint loadings that result from excess weight or obesity are associated with osteoarthritis of the knee joint [2]. Hence, a reduction of excessive joint loading may be beneficial for some users.

Some daily activities require greater muscle forces than those used for level walking, e.g., a sit-to-stand movement [3], and thus muscular strengthening of the lower limbs may be needed for the elderly or individuals with stroke. Although exercise with a partial BWS protocol

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(A) Pinnacle trainer (B) Body weight support system

Fig. 1. Fitness equipment used in this study.

may reduce muscular activation levels [4], BWS systems allow overweight or fragile individuals to exercise in the early intervention stage. Over time, the BWS levels can be decreased by clinicians in accordance with improvements in disease progression or the extent of weight loss. Weight bearing and muscle strengthening protocols are progressively added to intervention programs after improvements in disease progression to increase muscular strength for daily activities.

BWS is commonly combined with treadmills. The walking speed of stroke patients was found to increase after intervention with treadmill which combined with the BWS system [5,6]. However, individuals who have paretic legs may find it difficult to lift their legs during a gait training session. Thus, the integration of a BWS system and pedal-type exercise equipment would help users stabilize their feet on the pedals to provide reciprocal movements during rehabilitative training and prevent some abnormal gait patterns, such as foot drop or equinovarus, which may create a falling risk during intervention.

A pinnacle trainer (PT), a type of pedal-type exercise equipment, has exercise trajectories similar to those of a stair climber or stepper. Its advantages include biplanar exercise trajectories (on the sagittal and frontal planes; Fig. 1) and an adjustable pedal stance width (PSW). In a plantar pressure study, foot pressure in the medial arch was found to be significantly higher for a wider step width during walking [7]. The external knee adduction moment is reduced significantly during wider-step-width walking [8]. Therefore, the step width influences the force distribution in the lower extremities. Therapists usually adjust the amount of BWS by the correction of movements or alignment of the body in clinical practice. The establishment of the relationship between the amount of BWS and the joint loadings of the lower extremities might thus help clinicians better serve some specific groups. For example, therapists can select a suitable initial BWS level to decrease the joint loads for overweight individuals.

However, the biomechanical characteristics during stepping on a PT with different BWS levels for various PSWs are unknown. The relationship between the amount of the BWS and joint loadings should be established. Hence, the purposes of this study were to investigate the effects of BWS and PSW on the biomechanical characteristics of the lower extremities during stepping on a PT and to establish the association between the amount of BWS and joint loadings. This study hypothesized that the joint loads of the lower extremities may decrease with an increase in BWS level. In addition, the joint moments in the frontal plane might be influenced by PSW, and the joint resultant forces of the lower extremities might be associated with the amount of BWS.

2. Methods

2.1. Participants

Seventeen healthy adults (9 males) participated in the present study. The inclusion criteria were no present pain or discomfort in the lower extremities and a lack of any present musculoskeletal, neurological, or other disorders that might influence exercise. The basic demographic data of the participants are as follows: age: 22.17 ± 2.04 years, height: 165.58 ± 7.24 cm, and body weight: 54.56 ± 8.13 kg. The protocols used in this study were approved by the Institutional Review Board of National Cheng Kung University Hospital (IRB no: A-ER-101-060).

2.2. Instrumentation

A BWS system (S776MU, SportsArt, Taiwan) integrated with a PT (S776MA, SportsArt, Taiwan) was used in this study (Fig. 1).

A three-dimensional motion capture system with eight digital cameras (Osprey, Motion Analysis Corporation, USA) was used to record motion information. The sampling rate was set at 200 Hz during the experiment. Two six-axis force and torque transducers (Mini85, ATI Industrial Automation, USA) with a sampling rate of 2000 Hz were used to record pedal reaction forces (PRFs).

2.3. Procedures

Participants exercised on the PT under three BWS levels, namely 0%, 20%, and 40%, and three PSWs, namely narrowest (27 cm), medium (35 cm), and widest (44 cm). The BWS levels and PSWs were randomly selected. The investigators measured the participants' body weight and calculated the amount of supported weight for each level. The amount of BWS was directly read from the BWS system when the participants were standing statically on the pedals before data collection.

The average pelvis width and shoulder width of the participants were 27.41 ± 2.00 cm and 40.88 ± 2.16 cm, respectively. The widest and narrowest PSWs were selected to approximate the average shoulder width and the average pelvis width, respectively. Reflective markers were attached to the sacrum, bilateral anterior superior iliac spine, bilateral greater trochanter, bilateral mid-lateral aspect of the thigh, bilateral medial and lateral epicondyles of the knee, bilateral mid lateral aspect of the shank, bilateral medial and lateral malleoli of the ankle, bilateral middle base between the 2nd and 3rd metatarsal bones of the foot, and bilateral heel. To record the pedal motion during stepping, three reflective markers were placed on the lateral and posterior sides for each pedal. Participants were requested to step on the pedals with their feet fully in contact with the pedals during the exercise period at a constant cadence of 60 steps/minute. The load cells were embedded in the pedals of the PT during stepping for the measurement of the joint moments of the lower extremities. Since inconsistent stepping patterns may influence the joint moment measurements, to decrease the experimental bias from variation in the point of reaction force application, the participants were instructed to keep their entire foot on each pedal. Three trials were conducted with various BWS levels and PSWs, respectively. Fifteen seconds of data collection was conducted for each trial.

2.4. Data analyses

The step cycle was divided in two phases, namely the stepping phase and the recovery phase. The stepping phase was the period from the highest to the lowest pedal position, and the recovery phase was the period from the lowest to the highest pedal position. Data were normalized by the percentage of the step cycle.

Kinetics data were calculated using the inverse dynamic approach [9]. The peak PRFs, peak joint resultant forces, and peak internal joint moments of the lower extremities during the stepping phase were extracted and statistically analyzed.

2.5. Statistical analysis

All experimental data are expressed as means ± standard deviations (SDs). Two-way repeated-measures analysis of variance (ANOVA)

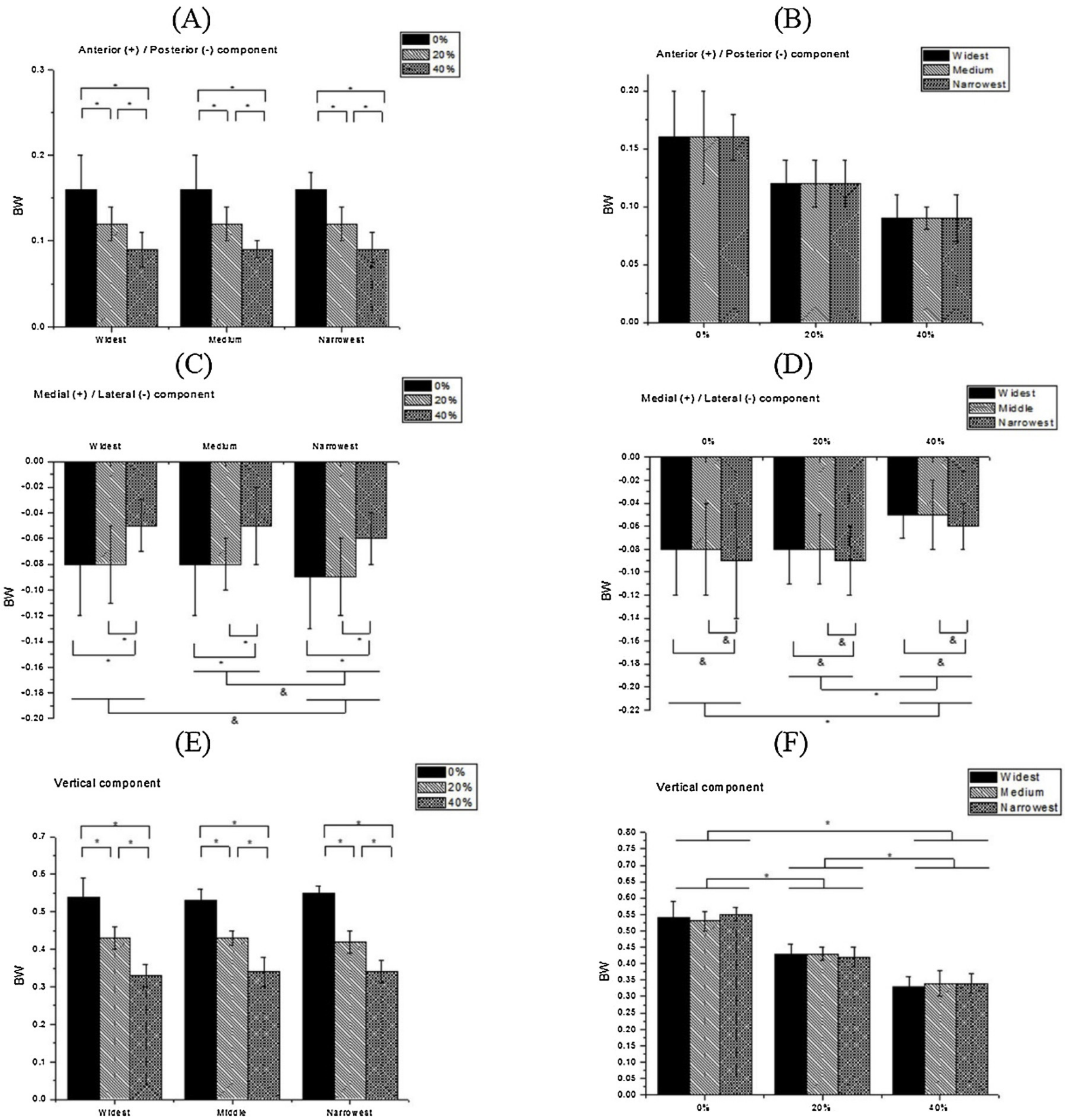

Fig. 2. Comparison of PRFs for various BWS levels and PSWs. Anteroposterior component comparisons for various (A) BWS levels and (B) PSWs. Mediolateral component comparisons for various (C) BWS levels and (D) PSWs. Vertical component comparisons for various (E) BWS levels and (F) PSWs. *: significant differences among BWS levels; &: significant differences among PSWs.

with least significant difference (LSD) post-hoc tests was used to examine the changes of biomechanical characteristics (including resultant forces, PRFs, and the joint moments of the lower extremities) among the different BWS levels (0%, 20%, and 40% of body weight) and PSWs (narrowest, medium, and widest). The significance level was set at 0.05.

When an interaction between BWS levels and PSWs was detected, the simple main effects of the BWS levels and PSWs were tested using one-way repeated-measures ANOVA with LSD post-hoc tests. Because the BWS levels and PSWs each had three conditions, the adjustment of the significance level according to Bonferroni correction was 0.05/3 (˜0.017), and thus the significance level was set at 0.017.

The association between the reduction of joint resultant forces and the amount of BWS was analyzed using the linear regression model. SPSS version 17.0 (SPSS Inc., USA) was used to perform the statistical analyses.

3. Results

The PRFs in the anteroposterior and the vertical components significantly decreased with increasing percentage of BWS (Fig. 2(A) and (E)). The mediolateral component showed a significant decrease with increasing percentage of BWS; however, there was no significant difference between the conditions of 0% BWS and 20% BWS (Fig. 2(C)). There were no significant differences among the various PSWs in terms of the anteroposterior and vertical components (Fig. 2(B) and (F)). Nevertheless, a significant lateral force was recorded during stepping with the narrowest pedal stance compared to those for the widest and medium pedal stances (Fig. 2(D)).

The joint resultant forces of the lower extremities showed significant decreases with increasing percentage of BWS (Fig. 3(A)–(E)). Significant differences between the widest and narrowest stances were found for the hip joint (Fig. 3(F)). There were no significant differences among the various PSWs for the ankle and knee joints (Fig. 3(B) and (D)).

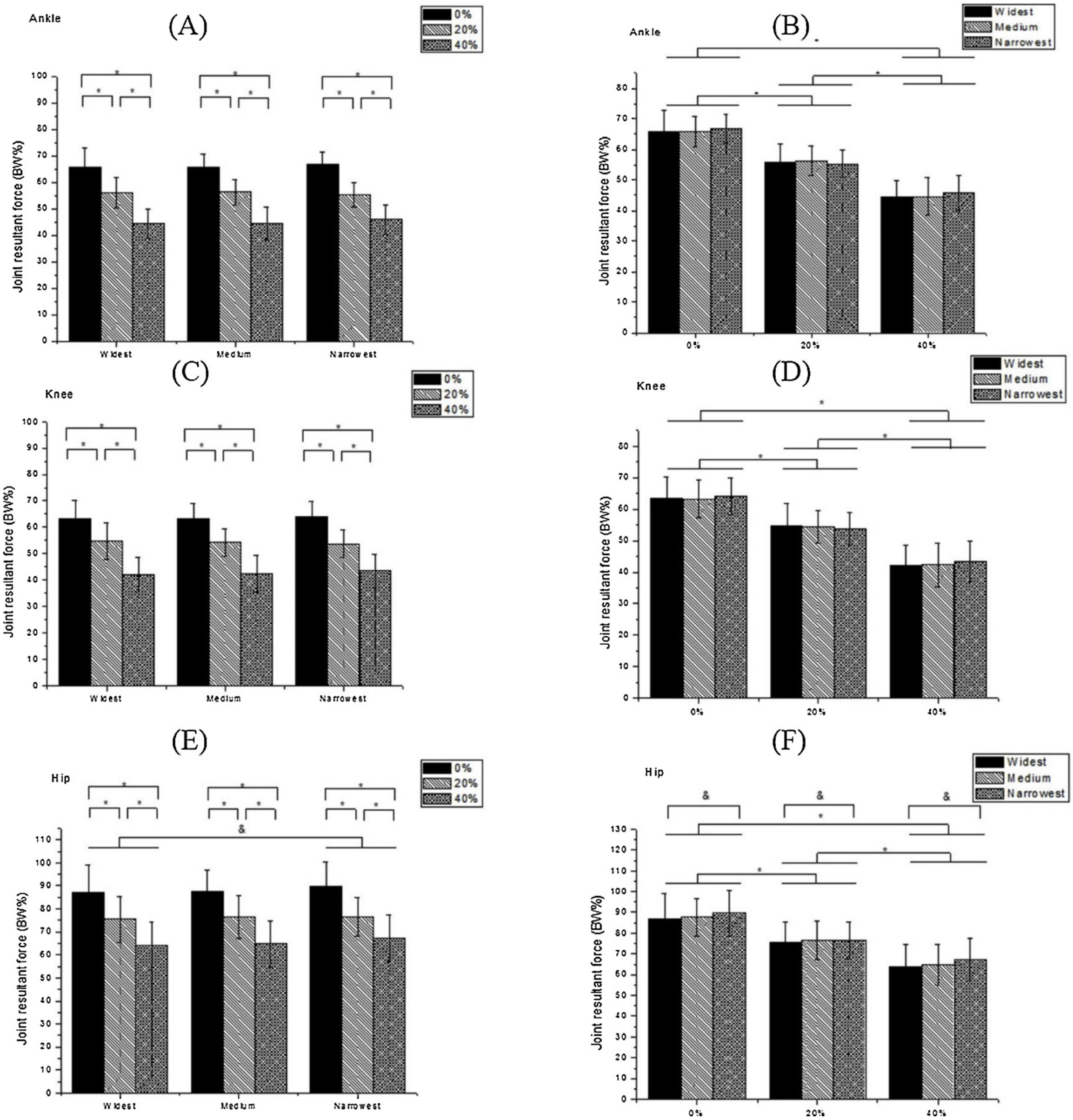

Fig. 3. Joint resultant force comparisons in the lower extremities among various BWS levels and PSWs. Ankle joint resultant force comparisons for various (A) BWS levels and (B) PSWs. Knee joint resultant force comparisons for various (C) BWS levels and (D) PSWs. Hip joint resultant force comparisons for various (E) BWS levels and (F) PSWs. *: significant differences among BWS levels; &: significant differences among PSWs.

The peak internal ankle plantar flexion moment significantly decreased with increasing BWS level, but no significant differences were found among the various PSWs (Fig. 4(A) and (B)). The peak internal knee extension moment showed no significant differences among BWS levels (Fig. 4(C)), whereas it decreased significantly with increasing PSW (Fig. 4(D)). In contrast to the peak internal knee extension moment, the peak internal knee flexion moment significantly increased with increasing PSW (Fig. 4(E)), but it showed no significant differences among BWS levels (Fig. 4(F)). For the hip joint, the peak internal hip extension moment decreased significantly with increasing BWS level. Significant differences in the peak internal hip extension moment were found between 0% and 40% BWS and between 20% and 40% BWS (Fig. 4(G)). The peak internal hip extension moment significantly increased with increasing PSW (Fig. 4(H)).

The internal ankle eversion moment significantly decreased with increasing percentage of BWS (Fig. 5(A)). There were no significant differences among the various PSWs in the ankle eversion moment (Fig. 5(B)). Nevertheless, significant interaction effects were found for the internal knee adduction moment and the internal hip abduction moment between BWS levels and PSWs. The internal knee adduction moment and the internal hip abduction moment significantly decreased with increasing BWS level with a simple main effect of BWS ($P < 0.016$) (Fig. 5(C) and (E)). With a simple main effect of PSW, the internal knee adduction moment for the widest pedal stance was greater than that for the medium pedal stance, which in turn was greater than that for the narrowest pedal stance across all BWS levels ($P < 0.016$) (Fig. 5(D)). With regard to the simple main effect of PSW on the internal hip abduction moment, exercise with the widest pedal stance produced a significantly greater internal hip abduction moment compared to that for the medium and narrowest pedal stances under 0% and 40% BWS ($P < 0.016$) (Fig. 5(F)). Under 20% BWS, the internal hip abduction moment significantly increased with increasing PSW ($P < 0.001$) (Fig. 5(F)).

In the simple linear regression analyses, the joint loading of the lower extremities tended to significantly decrease by about 1% of the joint resultant forces of body weight, when 1 kg of BWS was used for all

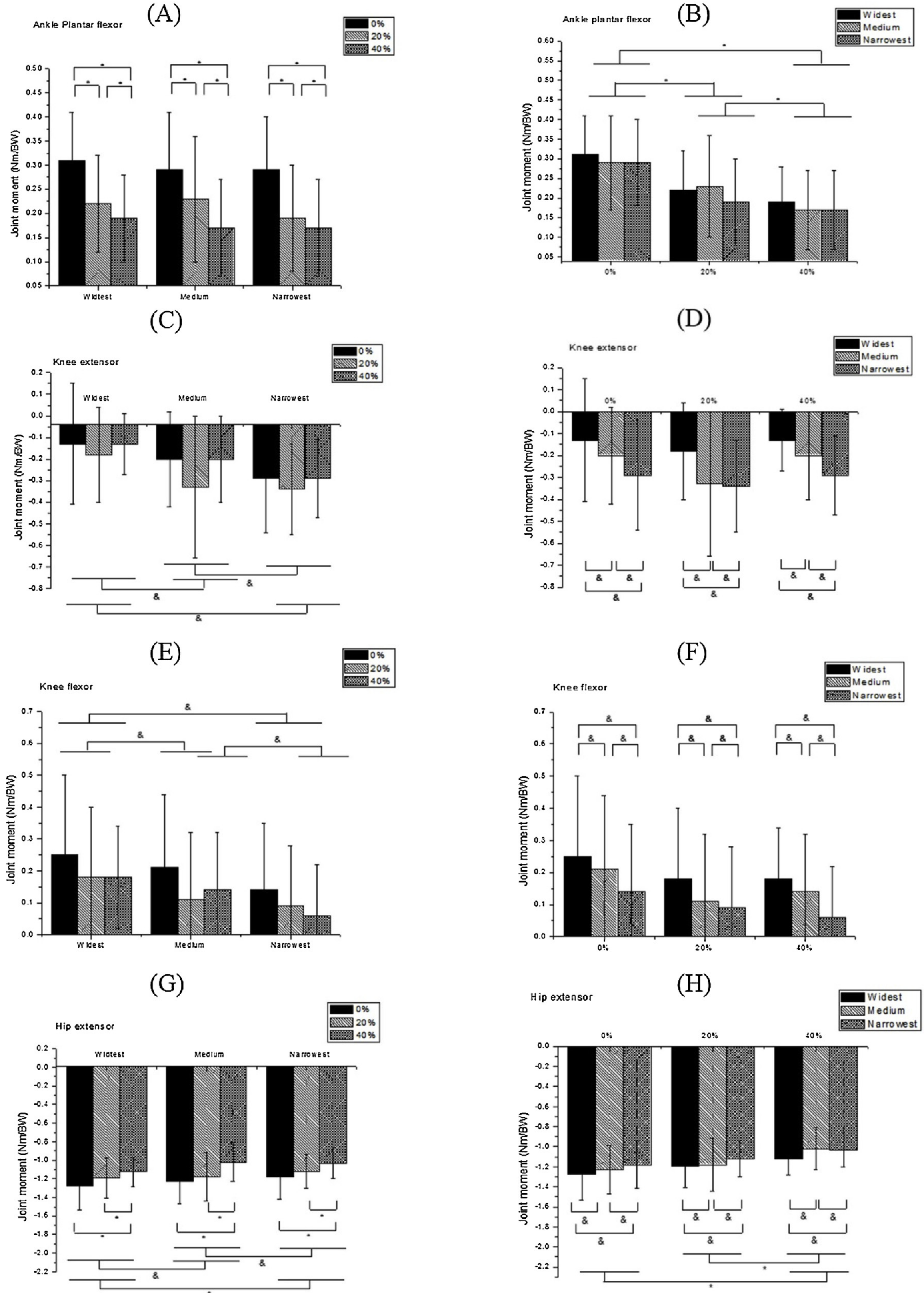

Fig. 4. Differences in sagittal plane joint moments of the lower extremities among various BWS levels and PSWs. Ankle plantar flexion moment comparisons for various (A) BWS levels and (B) PSWs. Knee extension moment comparisons for various (C) BWS levels and (D) PSWs. Knee flexion moment comparisons for various (E) BWS levels and (F) PSWs. Hip extension moment comparisons for various (G) BWS levels and (H) PSWs. *: significant differences among BWS levels; &: significant differences among PSWs.

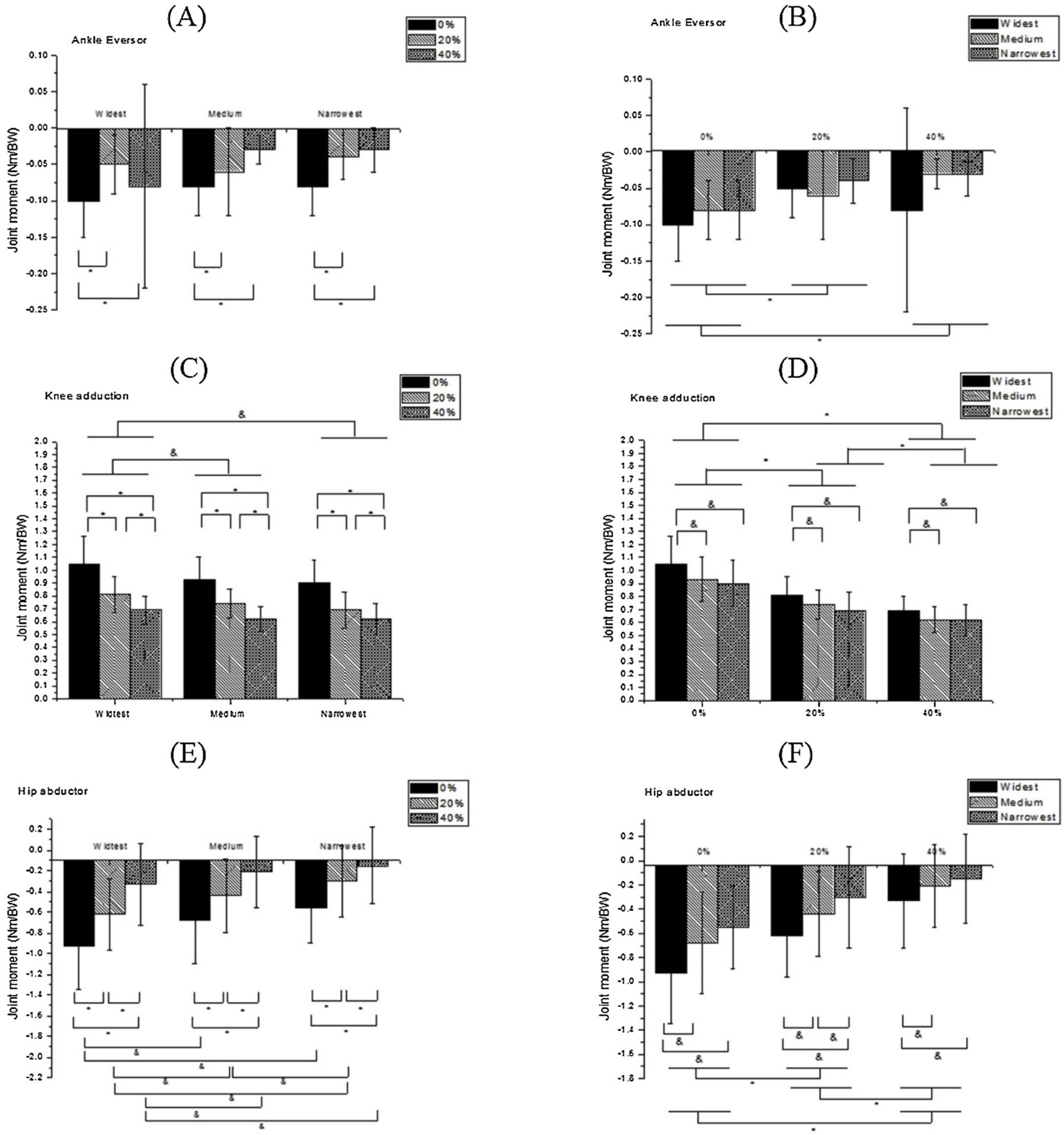

Fig. 5. Differences in frontal plane joint moments of the lower extremities among various BWS levels and PSWs. Ankle eversion moment comparisons for various (A) BWS levels and (B) PSWs. Knee adduction moment comparisons for various (C) BWS levels and (D) PSWs. Hip abduction moment comparisons for various (E) BWS levels and (F) PSWs. *: significant differences among BWS levels. &: significant differences among PSWs.

Table 1
Associations between changes in the amount of joint resultant forces of the lower extremities and changes in the amount of BWS for all PSWs. The explanatory variable (x) was the amount of BWS and the dependent variable (y) was the joint resultant forces.

Dependent variable (y)	Explanatory variable (x)	Slope (β)	T statistics	95% CI	P-value
Widest					
Ankle joint resultant forces (BW %)	Amount of BWS	−1.08	−7.72	−1.37 to −0.80	< 0.001*
Knee joint resultant forces (BW %)	Amount of BWS	−1.12	−6.12	−1.50 to −0.75	< 0.001*
Hip joint resultant forces (BW %)	Amount of BWS	−1.37	−5.85	−1.85 to −0.89	< 0.001*
Medium					
Ankle joint resultant forces (BW %)	Amount of BWS	−1.08	−7.83	−1.36 to −0.80	< 0.001*
Knee joint resultant forces (BW %)	Amount of BWS	−1.06	−6.44	−1.40 to −0.72	< 0.001*
Hip joint resultant forces (BW %)	Amount of BWS	−1.37	−6.45	−1.81 to −0.89	< 0.001*
Narrowest					
Ankle joint resultant forces (BW %)	Amount of BWS	−0.85	−6.48	−1.12 to −0.58	< 0.001*
Knee joint resultant forces (BW %)	Amount of BWS	−0.91	−5.76	−1.40 to −0.59	< 0.001*
Hip joint resultant forces (BW %)	Amount of BWS	−1.22	−5.7	−1.66 to −0.79	< 0.001*

* Significant relationship between joint resultant forces and BWS level.

PSWs (Table 1).

4. Discussion

The present study hypothesized that the joint loadings would decrease with an increase in BWS. The results showed significant decreases of joint resultant forces for the lower extremities across all PSWs. These results may be due to the decrease in the force exertion during stepping on a PT with an increase in the BWS level. Individuals with a history of stress fracture show a significantly greater impact force during running compared to those who do not have a history of stress fracture [10]. Thus, the greater impact force may be related to the injuries of the lower limbs. When stepping on a PT with or without BWS, the PRFs across all PSWs in the present study were smaller than those for exercise with an elliptical trainer and level walking [1]. Regarding the joint resultant forces, the hip joint resultant force during walking has been reported to be around 350% to 400% of body weight [11]. In the present study, the hip joint resultant force was less than 100% of body weight in all conditions. This might have resulted from the participants keeping their feet on the pedals throughout the whole exercise period while stepping on the PT, which eliminated the heel strike movements and further reduced the impulse load compare to those for level walking [12]. Moreover, the knee joint resultant force was less than 65% of body weight in all conditions in the present study; this value is smaller than those (65% to 131% of body weight) for stationary cycling at under 60 rpm [13]. Hence, from an injury prevention viewpoint, stepping on a PT may produce lower joint loadings than those for walking and cycling.

With increasing BWS level, the ankle and hip joint moments in the sagittal plane significantly decreased, which is consistent with a previous study, where significantly decreased joint moments for the ankle and hip joints were noted when participants walked on a treadmill with 0%, 20%, 40%, and 60% BWS [14]. The present study found that the knee extension moment significantly decreased with increasing PSW. This finding is similar to previous results of decreased knee extension moment of healthy participants ascending stairs with a wider step width [15]. In contrast, the knee flexion and hip extension moments significantly increased with increasing PSW. The lower reduction of the knee extension moment may be related to the increased ankle plantar flexion moment and greater hip extension moment, whereas the greater hip extension moment indicates a higher demand of hamstring activation [16]. Simultaneous contractions of the hamstring and the knee extensors have been found to decrease the loading on the knee joint [17]. Thus, the decreased knee extension moment and increased hip extension moment for the widest pedal stance may have generated smaller loading on the knee joint than that for the narrowest pedal stance.

The present study found that the internal knee adduction and the internal hip abduction moments significantly increased with increasing PSW, which is consistent with our hypothesis that the joint moments in the frontal plane are influenced by PSW. Individual with severe knee osteoarthritis (OA) have weak muscular strength of the hip abductor [18]. The weakness of the hip abductor results in drop hip and influences posture maintenance. Hence, drop hip increases the distance between the center of mass and the knee joint center, leading to greater knee adduction alignment and thus a greater external knee adduction moment [18]. Thus, a greater hip abduction moment may reduce the probability of knee OA progression [19]. Moreover, a greater external knee adduction moment increases knee joint loading on the medial compartment [20,21]. Moreover, people with knee OA also have a greater external knee adduction moment during walking compared to that for normal participants [22]. The magnitude of the external joint moment equals that of the internal joint moment but the direction is opposite. In the present study, the participants exercising with the PT produced an internal knee adduction moment equal to the external knee abduction moment. The external knee adduction moment has been shown to be a predictor for knee OA; nevertheless, exercise with the PT generates an internal knee adduction moment, which may be helpful for patients with knee OA to reduce joint loading on the medial compartment. Furthermore, exercise with a wider pedal stance generates a significantly greater internal knee adduction moment. Thus, clinicians or therapists can adjust the PSW for different severities of knee OA progression. Moreover, it is important for people with knee OA to strengthen the hip abduction muscles. Therefore, for people with knee OA, exercise with a wider PSW may be a better choice to strengthen the hip abductors due to a linear association between muscle activity and joint moment [23]. A greater hip abductor reduces the joint loadings on the medial compartment of the knee joint [19].

The joint resultant forces of the lower extremities are associated with the amount of BWS. The increased BWS level may decrease the force exertion during stepping on a PT; hence, the major variable may be the joint forces. For every kilogram of BWS, the joint loading of the lower extremities significantly decreased by about 1% of the joint resultant forces of body weight during exercise with the PT across all PSWs. Weight loss programs reduce the pain intensity and disability of overweight people with knee OA [24]. After weight loss, the internal knee abduction moment significantly decreases relative to the baseline measurement [25]. Obesity may increase joint loading, and thus exercise with a PT integrated with a BWS system may be a good choice for people who are overweight or obese and want to start a weight loss program.

4.1. Limitations and future work

This study recruited healthy, young, and normal-body-weight individuals, who are quite different from those who have a risk of falling, osteoarthritis, or obesity. Moreover, this study did not record electromyography data, and thus the relationship between muscle activity and joint moment could only be speculated based on previously reported results. Participants in this study stepped on the PT under a constant cadence for all conditions; however, the stepping speed may influence the joint moments.

Further investigation of the intervention effects on different user groups and the speed effects on joint loading is needed to develop suitable models for different groups (e.g., overweight people or people with lower limb injuries).

5. Conclusion

Exercise on the PT combined with partial BWS can effectively reduce PRFs, joint resultant forces, and joint moments of the lower limbs. Exercise with a wider pedal stance increased the internal knee adduction moment and the internal hip extension moment, which may decrease the potential of knee OA progression.

Declaration of Competing Interest

The authors have no conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2019.08.002.

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