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Effects of Backpack Load and Gait Speed on Plantar Force During Treadmill Walking

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Abstract. The purpose of this study was to examine the differences in the plantar force associated with changes in the backpack load and gait speed during treadmill walking. Nine healthy subjects without any known neurological or motor disorder participated in this study. The F-scan system Tethered system was used to collect plantar pressure data with a sampling frequency of 120 Hz. Subjects were asked to walk on a treadmill with varied levels of backpack load (0, 10%, 20% and 30% of body mass) and gait speed (4, 5, and 6 km/h). Under each task condition, subjects walked for approximately 3 min. During the last 20 s, the vertical ground reaction force (vGRF) data were collected. Our results showed that an increase in gait speed and backpack load leaded to increase in the magnitude of the first vGRF peak. Greater magnitudes of the second vGRF peak were only associated with an increase when gait speed was 4 km/h and 5 km/h. There were no speed-related changes in the magnitudes of the second vGRF peak at the speed of 6 km/h. The results of this study can provide clinicians with initial values with which to support physical therapist interventions to provide a greater health benefit.

Keywords: F-scan system, force-generating activities, osteoporosis

1. Introduction

The crude incidence of osteoporotic hip fracture was 244.8 per 100,000 person years from 2004 to 2006 in a Japan population aged 35 years or older. Predominantly due to falls, 30% individuals after a hip fracture become functionally dependent and require long-term nursing care. The incidences of osteoporotic hip fracture were increased in both men and women, when data was analyzed and compared with that from 30 years ago [1]. To protect against osteopenia and osteoporosis, studies of weight-bearing exercise may be of substantial clinical importance. They may be able to provide transmission and distribution information related to the vertical ground reaction force (vGRF) and exercise intensity. In particular, force-generating activities have been shown to produce significant effects on attaining optimal bone mass and bone strength [2].

Previous study shows that impact forces associated with walking are responsible for the load distributions of the musculoskeletal system [2]. The plantar pressure and force measurements allow for the dynamic analysis of the impact force at the foot-ground interface during walking. It can provide information about loading to skeletal regions and lower extremity alterations. There is evidence that shows the vertical ground reaction force (vGRF) is dependent on the external factors such as gait speed, carrying weight, shoes and surface involved. Since force-generating activities have positive effects on adaptive skeletal responses, the relationships among gait speed and carrying load with the vertical ground reaction force are important for understanding osteogenic effects on walking [3].

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A number of previous studies have evaluated gait adjustments under various load carrying conditions. Simonsen et al. compared bone-on-bone forces during unloaded and loaded walking at a self-paced speed. They found that 8.0% BW (body weight) peak compression force generated in the hip joint during loaded walking (20 kg) [4]. Kinoshita [5] and Knapik et al.'s [6] studies showed that knee flexion after impact was greater when carrying loads in order to absorb increased impact forces. Hsiang et al. recorded the vGRFs for a number of consecutive steps under three gait speeds and five load carrying positions. It was found that some loaded positions and higher speeds reduced the reliability of the execution of gait patterns while other loaded positions may actually increase gait stability [7].

Although a number of studies have found evidence to suggest that skeletal adaptation can be produced through loaded walking, the effectiveness of load carrying and gait speed remain unknown. Therefore, the purpose of this study was to assess the effect of backpack load and gait speed on treadmill walking, with a focus on the vertical ground reaction force. We were interested in whether the differences in mechanical adjustments are associated with changes in load and gait speed. Information from this study will help us to recommend suitable gait speed and backpack load to provide a greater health benefit.

2. Methods

2.1. Subjects

Nine healthy subjects, 5 males and 4 females, without any known neurological or motor disorders, participated in the experiment. Their mean age, height and mass were 27.4 years (±5.0 SD), 172.0 cm (±8.1 SD) and 69.4 kg (±11.8 SD), respectively. Subjects were informed about the experimental procedures and informed consent was obtained as per the guidelines of the University of Hiroshima.

2.2. Apparatus and Procedures

The F-scan® Tethered system (Tekscan Inc., USA) was used to collect plantar pressure data with a sampling frequency of 120 Hz. Subjects wore the same kind of walking shoes and the insoles were trimmed to their shoe size by cutting around its periphery to maintain the center of the insole to coincide with the center of the foot. The insole was connected via an amplifier attached to the subject's ankle. The plantar loading parameters were then transmitted from the F-scan transmission device to a laptop computer. The insole was calibrated for each subject using that subject's own weight before data collection.

Subjects were asked to walk on a treadmill (Powerjog, GXC200) for at least ten minutes to familiarity with the experimental environment and ensure equilibration in the temperature of the insoles. Each participant completed all 12 task conditions. One factor was weight load carried in the backpack (4 levels: 0, 10%, 20% and 30% of body mass). The second factor was gait speed (3 levels: 4, 5, and 6 km/h). Under each task condition, subjects walked for approximately 3 min. During the last 20 s, the vGRF data were collected. The order of task conditions was randomized for each participant.

2.3. Data Analysis

The foot contact and ground reaction forces served to determine the gait cycles. Step length was calculated using the equation for gait velocity (m/s) = step length (m/step)*cadence (step/s) and it was normalized with respect to each subject's height. The force signals were normalized as a percentage of body weight (% BW). The coefficient of variation (CV) was used to determine the vGRF variability from the consecutive steps. It was calculated as the standard deviation divided by the mean data value, multiplied by 100. The fractions of CV were transformed into z-scores for statistical analysis using Fisher's z-transformation.

All statistical analyses were carried out using SPSS statistical software (15.0J for Windows). Two-way ANOVA with repeated measures was used to examine the effect of the presence of backpack load (4 levels: 0, 10%, 20% and 30% of body weight), gait speed (3 levels: 4, 5, and 6 km/h). When necessary, a one-way ANOVA with repeated measures for each gait speed was performed. If a significant difference was detected, the polynomial test was performed at $\alpha=0.05$ level of significance to determine if a linear, quadratic or cubic trend existed.

3. Results

Although we analyzed the data separately over the gait cycle, there were no significant differences between steps with the left and right feet on any of the outcome measures. Therefore, results representing the averaged values of two feet will be reported.

Two-way ANOVA analysis showed that there was no significant speed-by-load interaction for the first vGRF peak (P1, Table 1) ($F(6,48)=2.0$, $p=0.091$). Main effects of gait speed ($F(2,16)=89.5$, $p<0.001$) and backpack load ($F(3,24)=35.1$, $p<0.001$) for P1 were confirmed. Trend analysis showed linear trends of P1 on gait speed ($F(1,8)=122.5$, $p<0.001$) and backpack load ($F(1,8)=54.2$, $p<0.001$) factors. Across gait speeds, an increase in backpack load resulted in an increased in P1.

Table 1: Mean and S.D. of the first (P1) and second (P2) peak of the vGRF (/Body Weight)

Gait speed	4 km/h				5 km/h				6 km/h			
Backpack load (% Body mass)	0%	10%	20%	30%	0%	10%	20%	30%	0%	10%	20%	30%
P1	1.17 (0.11)	1.26 (0.10)	1.34 (0.11)	1.45 (0.13)	1.33 (0.11)	1.44 (0.10)	1.54 (0.13)	1.61 (0.12)	1.56 (0.10)	1.73 (0.13)	1.80 (0.16)	1.89 (0.16)
P2	1.28 (0.06)	1.41 (0.09)	1.49 (0.09)	1.50 (0.10)	1.36 (0.08)	1.49 (0.13)	1.54 (0.11)	1.55 (0.10)	1.45 (0.13)	1.52 (0.14)	1.55 (0.12)	1.53 (0.19)

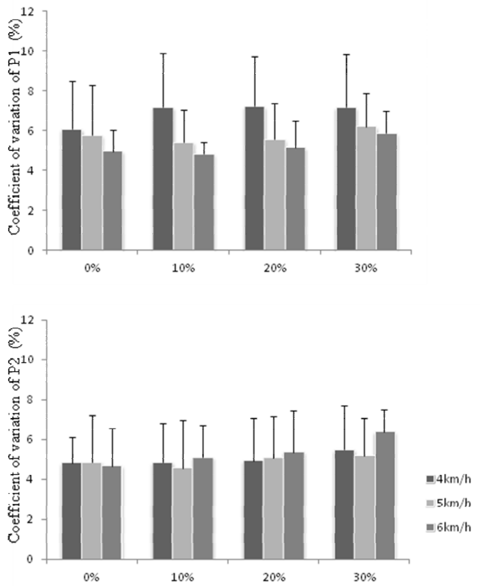

Fig. 1: Mean and S.D. of the coefficient of variation (CV) of the first (PI) and second (P2) peak of the vGRF across steps(%)

For the second vGRF peak (P2, Table 1), there was main effect of speed-by-load interaction ($F(6,48)=6.7$, $p<0.001$). The subsequent one-way ANOVA analysis showed a significant backpack load effect for gait speed of 4 km/h ($F(3,24)=41.2$, $p<0.001$) and gait speed of 5 km/h ($F(3,24)=27.2$, $p<0.001$). However, there was no significant load effect for gait speed of 6 km/h ($F(3,24)=2.9$, $p=0.053$). Trend analysis showed a liner trend ($F(1,8)=107.4$, $p<0.001$) of P2 for gait speed of 4 km/h. P2 value increased from 1.28 BW during no load walking to 1.50 BW when backpack load was increased to 30% of body mass. There was also a liner trend ($F(1,8)=95.9$, $p<0.001$) for gait speed of 5 km/h. P2 value increased from 1.36 BW during no load walking to 1.55 BW when backpack load was increased to 30% of body mass.

Figure 1 illustrates the coefficient of variation (CV) values of the step to step variation of vGRF from consecutive steps. All were well within the normal variability for experimental data of this type (<12.5%) [8]. The fractions of CV were further transformed into z-scores using Fisher's z-transformation for statistical analysis. Two-way ANOVA with repeated measures, with the factors *backpack load* (0, 10%, 20% and 30% of body mass) and *gait speed* (4, 5, and 6 km/h) were performed. There were no significant effects and no interaction for the z-scores of CV values of P1 and P2.

Two-way ANOVA analysis showed no significant speed-by-load interaction ($F(6,48)=0.58$, $p=0.0747$) on cadence (Table 2). There was a main effect of gait speed ($F(2,16)=108.2$, $p<0.001$) on cadence, such that cadence increased with gait speed increased. There were significant differences among each gait speed condition ($p<0.05$). For the step length, there was no speed-by-load interaction ($F(6,48)=0.97$, $p=0.454$). Gait speed showed a main effect ($F(2,16)=424.0$, $p<0.001$) on step length. Across backpack loads, step length increased with gait speed increased. There were significant differences in the 4 and 5 km/h conditions ($p<0.05$), the 5 and 6 km/h condition ($p<0.05$).

Table 2: Mean and S.D. of cadence (step/min) and step length (m) during gait

Gait speed	4 km/h				5 km/h				6 km/h			
Backpack load (% Body mass)	0%	10%	20%	30%	0%	10%	20%	30%	0%	10%	20%	30%
Cadence	107.1 (5.7)	110.1 (5.2)	110.2 (7.2)	114.2 (9.5)	115.5 (4.5)	116.3 (3.3)	118.3 (6.4)	122.8 (7.8)	124.4 (6.5)	124.6 (4.4)	128.0 (5.3)	132.1 (8.7)
Step length	0.62 (0.03)	0.61 (0.03)	0.61 (0.04)	0.59 (0.05)	0.72 (0.03)	0.72 (0.02)	0.71 (0.04)	0.68 (0.04)	0.81 (0.04)	0.80 (0.03)	0.78 (0.03)	0.76 (0.05)

4. Discussion

This study extends recent work on force-generating activities [2,9], providing a further test that impact force changes with backpack load and gait speed. Our experiment has shown that an increase in gait speed and backpack load leaded to increase in the magnitude of the first vGRF peak. Greater magnitudes of the second vGRF peak were only associated with an increase when gait speed was 4 km/h and 5 km/h. There were no speed-related changes in the magnitudes of the second vGRF peak at the speed of 6 km/h. These findings are important for the purpose of constituting the load-bearing walking programmes for protecting against osteopenia and osteoporosis.

Chao and colleagues provided the largest set of normative data on 148 normal subjects of GRF parameters in adult level walking. Generally, the magnitude of the two force peaks during level gait was reported between about 1.1 and 1.3 BW [8,10]. Our data are consistent with the previous findings. It would suggest that analysis of treadmill gait in the present study is functionally equivalent to evaluating overground gait.

During gait, the foot-ground contact force counteracts the gravitational force of the moving body. The vGRF shows a rapid rise at the heel contact to a value (P1) in excess of body weight as full weight bearing takes place. At the pre-swing phase, the plantarflexors are active in generating ankle plantarflexion movement, which causes a second peak (P2) greater than body weight [11]. The increases in the magnitude of the vGRF peaks as gait speed and backpack load increased likely reflects an effort by the gait control system to maintain dynamic body stability with respect to the challenge task conditions. In the study by Majumdar et al. [12], 3-D Motion Analysis System was applied to kinematic parameters of gait whilst carrying different loads (6.5-27.2% body weight). They found that the ankle was more dorsiflexed, the knee and hip were more flexed during foot strike and helped in absorption of increased impact forces, and it has been suggested that an adaptive phenomenon to counterbalance load carrying effect.

Evidence shows that vGRF is linearly associated with the strain generated in bone [13]. Higher strain may contribute to larger osteogenic responses [14,15]. A number of studies have shown that even moderate impact force may be osteogenic effective [16]: a significant increase in bone mineral density has been reported with postmenopausal women walking 1 mi/day [17]. Burr et al.'s experiment found that exercise involving repetitive loading of 1.5 times body weight of the lower limbs could be used to treat or prevent age-related osteoporotic changes in the vertebrae [2]. Under the backpack load condition, the magnitudes of vGRF were above that of unload walking: the magnitudes of two vGRF peaks were both greater than 1.5 times body weight at 6 km/h. In combination with the factor of gait speed, it would suggest that 20% of body weight load-bearing walking at 5 km/h have an optimal influence on osteogenic effects.

The analysis in this study has shown gait length and cadence increased with gait speed and load increased. This is true with respect to the normal subjects. We have not considered age effects on cadence and gait length. In general, the same expectations wouldn't work with people age primarily because cadence increases to the adaptation more than step length. We take it as a major limitation of the study. Since it is an important point to be considered as constituting the load-bearing walking programme, this seems a natural future development of this line of research to explore age effects of different gait speeds and loads on the vGRF.

5. Conclusions

In summary, the findings on vGRF parameters indicate that an increase in the first vGRF peak with increased gait speed and heavier backpack could be an adaptive mechanism on the musculoskeletal system in terms of possible higher lower limb impact forces. Results also showed similar CV values of the step to step variation of vGRF indicating adjustment to maintain dynamic balance for challenging conditions. These findings might be useful in a clinical setting. The vGRF data from this study can provide clinicians with initial values with which to support physical therapist interventions to maintain and improve bone mass and bone strength. We suggest that backpack load walking may be a complementary approach for protecting against osteopenia and osteoporosis.

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