 Original Article

Effects of Load Carrying Methods and Stair Slopes on Physiological Response and Postures during Stairs Ascending and Descending

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Abstract: The purpose of this study was to examine the effects of load carrying methods, stair slopes and walking speeds on heart rate and walking postures. Nine participants climbed up and down stairs with various stair slopes (24°, 30° and 36°), walking speeds (72, 96, and 132 steps per minute), and using different load carrying methods (empty loads, backpack, and hand-held). The effects of these factors on heart rate, Borg-RPE and flexion angles of knee joints, hip joints and trunk angles were investigated. This study demonstrated that increased stair slopes and walking speed were associated with increased heart rate and RPE. The heart rate for empty loads subjects was lowest, followed by backpack load and hand-held load. Climbing stairs with larger inclination was associated with smaller knee joint flexion angle and larger trunk and hip joint flexion angle. In conclusion, it is easier for subjects to carry a load of the same weight up stairs by backpack than by hand. However, the stair slope should be less than 30°. Thus, the standard fixed stair slope (30° of stair slope) on recommended for riser height and tread depth are 160 mm (6.5 inches) and tread depth 280 mm (11 inches).

Key words: Heart rate, Load carrying method, Stair climbing, Stair slope

Introduction

Stairs climbing is a frequent occurrence within daily life, but the percentage of tripping and falling event on stairs is quite high[1–3]. Attention to the design of stairs cannot be expected to eliminate all of these incidents because many are related to inattention or risk-taking behavior. However, good design can reduce the potential for misstepping or provide a person about to fall with a way to retrieve balance. Many aspects of stairway design have been identified as important to safe stairway use including: inclination, stair riser height and uniformity, tread depth and width, tread overhang and configuration, lighting, vista, approaches, landings, surface materials and handrails. Designs that are pleasing to the eye may be hazardous because they do not take into account normal walking gait or expected step height. Additional concerns relate to the characteristics of people who use stairways: age, anthropometrics, physical condition, apparel, and task attention[4–6].

It is sensible to have the stairs designed in such a way that they can be ascended and descended as efficiently as possible. A stairway that is not difficult to ascend may be very difficult to descend[6]. This is particularly important when the stairs are in frequent use or used by infirm or elder people[7, 8]. The most common injuries caused by stairs accident are the fractures caused by tripping or falling[9]. The increment of inclination can cause danger easily under distracted conditions, and even increase falling and death rates[10–12]. Previous studies of stair ascent and descent have investigated on effects of stair inclination[12–14], knee and hip moments[15, 16], ground reaction forces and frictional demands[1], and foot clearance[17]. Stair climbing has also been investigated as a gymnastic exercise

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in preventive medicine[18, 19]. In addition, Liu and Chou compared three carriage modalities (backpack, satchel and handbag) and found that backpack carriage of loads equivalent to 10% body weight by incurred the lowest physiological cost while walking at 6.4 km/h[20]. Laursen *et al*. measured oxygen consumptions of individuals while walking either horizontally or up and downhill at an 8% slope under carrying loads in hands. Their study showed that oxygen consumptions rate of walking uphill increased by more than 70% compared with carrying loads horizontally[21]. Liu also reported that a significant interaction was found between grade level and load position[22]. There are, however, very few investigations of the relationship between stairs climbing within the various methods of carrying loads and walking speed.

Dimensions of stair geometry include riser height, tread depth, inclination, handrail, stair width, illumination and coefficient of friction. The riser height is the vertical distance between two consecutive treads or between a tread and a landing. The tread depth is the horizontal distance between two consecutive nosings. The inclination, the angle between a line joining consecutive nosings and the horizontal, can be controlled by tread depth and riser height. Since walking with equally sized steps is more comfortable and safe, the floor-to-floor height should be an exact multiple of the riser height. Nagata used sensory tests to evaluate the rational index of various tread/rise combinations[23]. Kroemer and Grandjean recommended that the least energy was consumed when climbing stairs with an inclination of 25–30°, and recommended the following empirical norms: riser height 170 mm, tread depth 290 mm[7]. Stairs of these dimensions are not only the most efficient but also seem to cause the fewest accidents. This recommendation can be expressed as an optimum formula: $2h+d = 630$ mm, where h=height of riser and d=depth of tread, both in mm. Roys found that this formula $2h+d$ is limited between 550 and 700 mm[2]. Jackson and Cohen considered that the 8-inch (20.32 cm) riser and 9-inch (22.86 cm) tread residential stair standard, preferred by some builders in United States, is too divergent from the "7–11" (7-inch (17.78 cm) risers and 11-inch (27.94 cm) treads) recommendations indicated by many safety studies[24]. In stair climbing, the stair dimensions are the environmental measures that the perceiver needs to take into account. Stairs can be constructed with different inclinations: from the deep tread with low riser height, as is typically found in elementary schools and public buildings, to the shallow tread with height riser, as is typically found in residential stairs. By the same token, people have different anthropometrical measures, which change within the individual's life span[10]. The point is that stair climbers need to be ready to approach different stair sizes at any moment in their life.

For safety considerations, designing stairs to conform to most people's demands is worth studying. Ascending and descending stairs affects heart rate and the flexion angles of the knee joints, hip joint and trunk to extents which depend on stair inclination, climbing speed and differences in load carrying methods. However, few investigations of the relationship between stairs climbing within the various methods of carrying loads and walking speed. Thus, the purpose of this study was to examine the effects of load carrying methods, climbing speeds and stair inclination on heart rate and walking postures.

Methods

Participants

The study was approved by the Research Ethics Committee of the researcher's institution. Nine male undergraduate students were recruited from St. John's University, serving as paid volunteers during the study. Their mean (SD) age was 22.4 (0.49) yr old, mean stature was 170.4 (9.56) cm, mean body weight was 63.8 (11.54) kg. All participants were healthy and reported no musculoskeletal problems or cardiovascular disease which might have detrimentally influenced their performance.

Apparatus and materials

The experimental equipment used in this study included three shape sensors (S700, Measurand, USA), moment capture system (CAPTIV L3000, TEA, France) and related measuring instruments (a metronome, a stopwatch), and notebook computer (Acer TravelMate 5720, Taiwan). A Polar electrode belt was placed around the chest and used to continuously measure the heart rate of subjects during experiments (Polar Vantage NV, Finland). Further, three shape sensors were applied to measure the angles of knee joint, hip joint and trunk during ascending and descending stairs, respectively. As shown in Fig. 1, the transmitter unit was attached on the trunk and sending the data by wireless to the receiver in a radius of 100 m in open ground. In addition, a receiver unit was connected on notebook computer for recording.

Experimental procedures

Experiments were carried out for two weeks during the day in July. Mean temperature is 29.2°C (25.8–34°C) and mean relative humidity is 74%. In addition, participants have worn the fitted shorts (e.g. swimming or

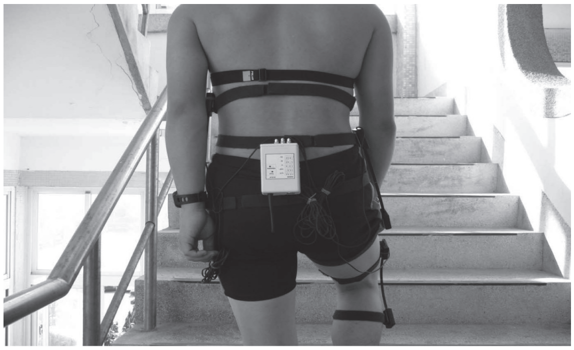

Fig. 1. Participant with measuring instrument.

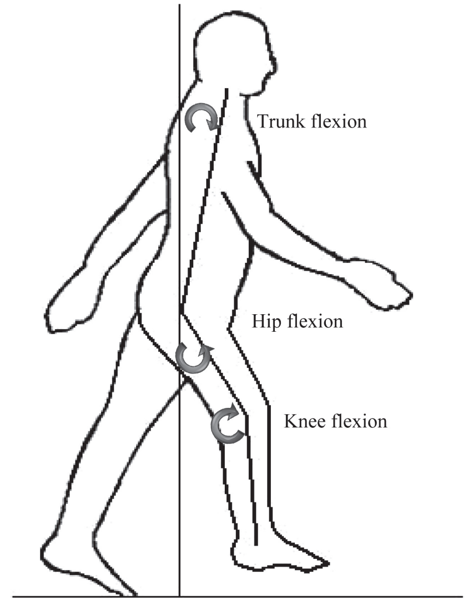

Fig. 2. Flexion angles of hip joint, knee and trunk defined in present study.

cycling shorts) to avoid interfering with data recording of walking postures. Before commencement of actual experiments, the participants were given time for warm-up, practicing ascending and descending stairs, and familiarizing themselves with experimental tasks until they were able to steadily perform all required movements. Further, three shape sensors were then mounted on the knee joint, hip joint and trunk of each participant and signal receivers were checked to ensure each wire was properly connected and the signal was being delivered to the computer. A total of 27 trials were performed for each participant at three stair inclinations, three walking speeds, and with three load carrying methods (empty loads, backpack, and hand-held).

Stair slopes were divided into three levels (24°: riser height 130 mm, tread depth 290 mm; 30°: riser height 160 mm, tread depth 280 mm; and 36°: riser height 176 mm, tread depth 242 mm). The walking speed was set at three levels: fast (132 steps per minute), middle (96 steps per minute), and slow (72 steps per minute). In order to control the walking speed, a metronome was used to set the pace. Each participant was asked to take one step on the stairs for each metronome beat. In addition, the nylon backpack ($31 \times 54 \times 14$ cm, $L \times H \times W$) that has the handle belt in top was used in this study. Further, load carrying was applied by three methods (empty loads, backpack and hand-held). The load to be backpacked and hand-held was a bag filled with books to obtain a total pack weight of 10% of each participant's body weight (5–7.5 kg). Furthermore, the load was held on right hand only during trials while carrying load by hand-held.

After each experimental condition was analyzed, participants reported their psychophysical response with a perceived exertion (Borg-RPE) rating[25]. The scales that are constructed 15-points ratings from 6 (no exertion at all), 7, 8 (extremely), 9 (very light), 10, 11 (light), 12, 13 (somewhat hard), 14, 15 (hard, heavy), 16, 17 (very hard), 18, 19 (extremely hard), and 20 (maximal exertion) are linearly related to heart rate expected for that level of exertion (expected heart rate is 10 times the rating given).

The order of these trials was randomly assigned for each subject. In addition, each trial involved walking for at least 10 min or more (if required) until physiological measurements stabilized. A minimum rest period of 30 min (more if required) was provided between trials until baseline physiological indices were restored. During the rest periods, participants were asked to stay seated, relax and remain silent. If baseline measurements could not be achieved after a rest period, the experimental session was resumed the next day.

Data analysis

A randomized complete block (each subject) design with three within-subject factors (stair slope, walking speed, and load carrying method) was used in this study. Heart rate was calculated from the ECG recordings by Polar software. Postures data were recorded by motion analysis system. The flexion angles of hip joint, knee joint and trunk were described in Fig. 2. In addition, all trial data files were exported in Microsoft Excel format, with the peak values for each motion axis on hip flexion, knee flexion, and trunk flexion were calculated over trials. Although each trial was carried out for at least 10 min or more (if required) until physiological measurements stabilized, only last one minute data were used for analyzing. For heart rate, Borg-RPE and flexion angles of trunk were considered as averaged during ascending and descending. Finally, multivariate analysis of variance (MANOVA) was utilized to identify significant differences between conditions for dependent variables. Statistical significance was set at a probability level of 0.05.

Results

The mean (standard deviation) values for physiological responses and subjective ratings during stairs ascending or descending are presented in Table 1. Further, the mean (SD) values for walking postures during stairs ascending or descending are also presented in Table 2. Finally, multivariate analysis of variance (MANOVA) was conducted for the seven measures. Further results have been presented as follows.

Effect of stair slopes

Results of MANOVA revealed a significant main effect of stair slopes (Pillai's trace=0.81, F(14, 422)=20.41, $p<0.001$, partial $\eta^2=0.404$) on 1.000 of statistical power (alpha=0.05, two-tail). Univariate F tests showed significant differences in heart rate (F(2, 216)=46.431, $p<0.001$), RPE scales (F(2, 216)=55.912, $p<0.001$) between stair slopes. Duncan's multiple range tests indicated that there were higher heart rate and RPE in 36° and 30° of stair inclination than in 24° of stair inclination. Results of analysis showed that significant increases for angles of trunk flexion (F(2, 216)=38.6,

Table 1. Mean, standard deviation and statistical comparison for physiological responses and subjective ratings stratified by experimental conditions

	Heart rate (beats/min)	RPE (Scales from 6–20)
Stair slopes		
24°	139.4 A (18.1)*	11.7 A (3.1)
30°	145.6 B (18.3)	14.4 B (3.4)
36°	152.4 C (11.1)	14.5 B (3.2)
Walking speeds		
Slow	140.4 A (17)	12.4 A (3.2)
Middle	146.5 B (17.1)	13.5 B (3.1)
Fast	150.7 C (15.4)	14.9 C (3.6)
Carrying methods		
Empty loads	141.3 A (17.2)	11.2 A (2.9)
Backpack	147.2 B (16.7)	14.1 B (2.9)
Hand-held	149.1 B (16.3)	15.5 C (3.2)

A, B, C are Duncan's multiple range test groups.
* Standard deviation presented in parentheses.

Table 2. Mean, standard deviation and statistical comparison for postures stratified by experimental conditions

	Trunk flexion	Hip flexion while ascending	Hip flexion while descending	Knee flexion while ascending	Knee flexion while descending
Stair slopes					
24°	19.1 A (7.8)*	59.2 A (13.6)	31.8 A (14.5)	79.0 B (20.9)	77.9 B (20.2)
30°	31.9 B (14.3)	63.1 A (14.5)	43.6 B (15.9)	83.9 B (15.4)	83.8 C (17.7)
36°	34.1 B (16.8)	75.5 B (19.4)	59.3 C (29.7)	75.0 A (14.7)	72.2 A (19.8)
Walking speeds					
Slow	28.8 (16.6)	65.3 (17.9)	43.4 (25.1)	81.4 (19.6)	79.9 (19.5)
Middle	27.3 (13.9)	65.1 (16.9)	44.4 (23.8)	78.0 (16.8)	77.7 (20.1)
Fast	28.9 (14.4)	67.3 (15.6)	46.9 (22.9)	78.5 (16.0)	76.2 (19.7)
Carrying methods					
Empty loads	28.4 (15)	62.0 A (18.1)	42.3 A (25.1)	81.0 (16.1)	80.5 B (22.1)
Backpack	29.8 (12.3)	66.3 B (17.4)	42.8 A (22.7)	77.3 (17.1)	78.5 AB (18.4)
Hand-held	26.4 (16.5)	69.4 B (16.2)	49.6 B (23.5)	79.6 (19.2)	74.9 A (18.3)

A, B, C are Duncan's multiple range test groups.
* Standard deviation presented in parentheses.

$p<0.001$), when stair slope was increased from 24° (19.1, SD=7.8) to 30° (31.9, SD=14.3) and 36° (34.1, SD=16.8). During ascending stairs, the larger flexion angles of hip joint were showed while ascending and descending on 36° of stair slope. By contrast, there were smaller significant knee flexion angles while ascending and descending on 36° of stair slope.

Effect of walking speeds

As expected, there were significant increases in heart rate ($F(2, 216)=29.27$, $p<0.001$) when the walking speed was increased from slow speed (140.4 beats/min, SD=17.0) to middle slow (146.5 beats/min, SD=17.1) and fast speed (150.7 beats/min, SD=15.4). Duncan's multiple range test indicated that the RPE scales were higher in fast speed (14.9, SD=3.6), middle speed (13.5, SD=3.1) than in slow speed (12.4, SD=3.2). By contrast, the flexion angles of knee joints, hip joint and trunk were not significant difference between walking speeds.

Effect of load carrying methods

Results of MANOVA also revealed a significant main effect of load carrying methods (Pillai's trace=0.653, $F(24, 412)=8.33$, $p<0.001$, partial $\eta^2=0.327$). Univariate F tests showed significant differences in heart rate ($F(2, 216)=17.69$, $p<0.001$), RPE scales ($F(2, 216)=106.86$, $p<0.001$) between load carrying methods. The heart rate increases significantly while the load carrying methods was changed from empty loads (141.3 beats/min, SD=17.2) to backpack (147.2 beats/min, SD=16.7) and hand-held load (149.1 beats/min, SD=16.3). Duncan's multiple range test indicated that the RPE scales were higher in fast speed (14.9, SD=3.6), middle speed (13.5, SD=3.1) than in slow speed (12.4, SD=3.2). Results of analysis for walking postures, the hip flexion angles were significant increase while carrying loads by hand-held method during ascending and ascending. In addition, the knee flexion angles were decrease while carrying loads by hand-held method during stairs ascending.

Interaction between stair slope and load carrying methods

The interesting result from the viewpoint of heart rate was the significant interaction between stair slopes and load carrying methods ($F(4, 216)=4.7$, $p<0.001$; Fig. 3). For empty loads condition, these were not significant difference in heart rate on 24° and 30° of stair slope. By contrast, heart rate increased dramatically on the 36° of stair slope. For carrying loads condition, there was no significant difference in heart rate on 24° of stair slope. However, the heart rate was the highest for hand-held method on 30° of stair slope. On the other hand, subjects had increased physiological loads while carrying loads by backpack on 36° of stair slope. In addition, trunk flexion angles were increases depending increment of stair slope. These were lower trunk flexion angles while carrying loads by backpack (Fig. 4).

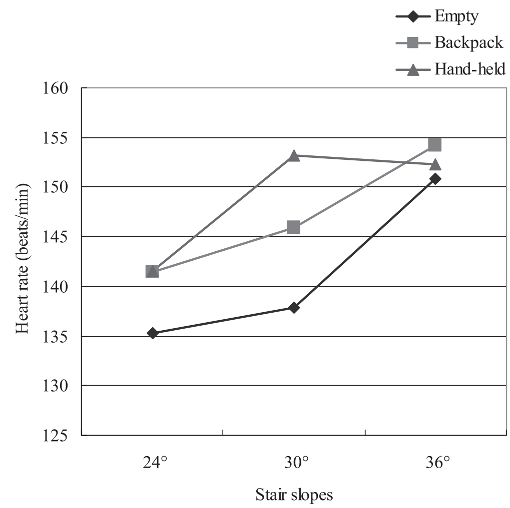

Fig. 3. Interactive effect between stair slopes and load carrying methods on heart rate.

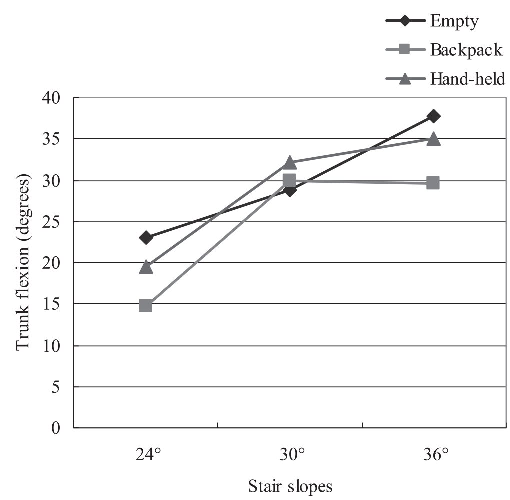

Fig. 4. Interactive effect between stair slopes and load carrying methods on trunk flexion.

Interaction between walking speeds and load carrying methods

A significant interactive effect on heart rate was found between walking speed and load carrying method ($F(4, 216)=3.676$, $p<0.05$) (Fig. 5). Heart rate was affected significantly by walking speeds rather than by load carrying method while fast walking speed particularly (132 steps/min).

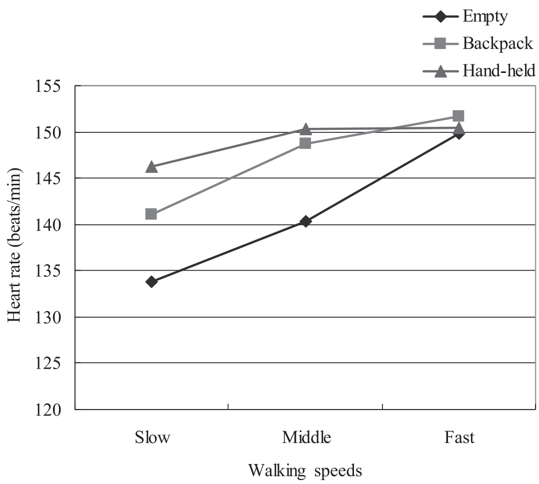

Fig. 5. Interactive effect between walking speeds and load carrying methods on heart rate.

Discussion

As expected, heart rate increased with the increment of stair slope and also with walking speed. Nagata reported that steep stairs with high rises and small treads demand no more metabolic loads than less steep stairs with much lower rises and larger treads[23]. Liu also revealed that walking on a 6% grade was associated with higher oxygen consumption and heart rate compared to level going[22]. Laursen *et al*. measured oxygen consumptions of individuals while walking either horizontally or up and downhill at an 8% slope under carrying loads in hands. Their study showed that oxygen consumptions rate of walking uphill increased by more than 70% compared with carrying loads horizontally[21]. Navalta *et al*. also reported that cardiovascular and metabolic responses were highest at 5% grade compared with level and downhill walking[26]. Investigation of joint flexion angle during stair climbing in this study showed that the knee joint flexion angle was smaller when subjects were climbing at the higher stair slope. In contrast, the hip joint flexion angle was increase when climbing the higher stair slope. The trunk flexion angle was larger when climbing a greater stair slope.

For carrying methods, Liu and Chou compared three carriage modalities (backpack, satchel and handbag) and found that backpack carriage of loads equivalent to 10% body weight by incurred the lowest physiological cost while walking at 6.4 km/h[20]. Results of present also showed that the heart rate was lowest when no load was carried, followed by backpack load and hand-held load. The rating of perceived exertion was also similar for the two load carrying methods. Liu also reported that where participants were walking at zero incline, there was no significant difference in mean oxygen consumption. By contrast, the mean oxygen consumption was significantly higher where loads were carried in the upper position and negotiating the 6% grade[22]. Load and gradient are associated with forward postural inclination. The lateral force of backpack load may act directly on the rear part of the trunk during inclination. This appears to produce greater restriction of the thorax, particularly while walking up an inclined grade with the load in the high position. In addition, Bobet and Norman have reported that higher load placement (shoulder level) results in significantly elevated levels of muscle activity (below mid-back)[27]. Results of present study showed that the trunk flexion angle was larger when climbing a greater stair slope. Furthermore, comparison of carrying loads methods revealed that trunk flexion angle was lower in applying the backpack load than other load conditions. Load carriage mainly produces a vertical force on the shoulders to maintain an erect trunk.

Conclusions

This study demonstrated that increased stair slope and walking speed were associated with increased heart rate. The heart rate for empty loads subjects was the lowest, followed by backpack load and hand-held load. The rating of perceived exertion and heart rate were well correlated in these experiments. Climbing stairs with larger inclination was associated with smaller knee joint flexion angle and larger trunk and hip joint flexion angle. Conversely, climbing the stairs with smaller inclination was associated with larger knee joint flexion angle and smaller hip joint flexion angle.

In conclusion, this study demonstrated that climbing lower stair slopes is perceived as easier while climbing steeper stairs is perceived as more tiresome. This study also demonstrated that it is easier for subjects to carry a load of the same weight up stairs by backpack than by hand. However, the stair slope should be less than 30°. Thus, for standard fixed stair slope (30° of stair slope) on recommended for riser height and tread depth are 160 mm (6.5 inches) and tread depth 280 mm (11 inches)[28]. In addition, slopes below 20° are for ramps, and above 50° are for stair ladders. It is important for engineering designers in the housing industry to consider the design of stairways with suitable stair slope. Such implications might involve the need to consider the effects of inclination and likely walking speed on physiological workload and joints in specific populations (such as elderly) when designing stairways. Stair slope, riser height, tread depth, surface materials and handrails are important considerations in a stairway design. Future research should clarify, confirm and expand on our findings using experiments involving ramp design, stair ladders design and handrails.

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