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Does Strategy of Downward Stepping Stair Due to Load of Additional Weight Affect Lower Limb's Kinetic Mechanism?

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Abstract

This study measured the downward stepping movement relative to weight change (no load, and 10%, 20%, 30% of body weight respectively of adult male (n=10) from standardized stair (rise of 0.3 m, tread of 0.29 m, width of 1 m). The 3-dimensional cinematography and ground reaction force were also utilized for analysis of leg stiffness: Peak vertical force, change in stance phase leg length, Torque of whole body, kinematic variables. The strategy heightened the leg stiffness and standardized vertical ground reaction force relative to the added weights (p<.01). Torque showed rather larger rotational force in case of no load, but less in 10% of body weight (p<.05). Similarly angle of hip joint showed most extended in no-load, but most flexed in 10% of body weight (p<.05). Inclined angle of body trunk showed largest range in posterior direction in no-load, but in vertical line nearly relative to added weights (p<.001). Thus the result of the study proved that downward stepping strategy altered from height of 30 cm, regardless of added weight, did not affect velocity and length of lower leg. But added weight contributed to more vertical impulse force and increase of rigidity of whole body than forward rotational torque under condition of altered stepping strategy. In future study, the experimental on effect of weight change and alteration of downward stepping strategy using ankle joint may provide helpful information for development of enhanced program of prevention and rehabilitation on motor performance and injury.

Keywords: *Ankle strategy, Step landing, Leg stiffness, Load, Whole body torque, Rehabilitation program*

1. Introduction

Carrying weight was difficult task even though during level gait [1, 2], but furthermore its task was spotted frequently during stair gait [3]. Also various injury during stair gait (up and down) under various heights of

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stair had been commonly occurred in the course of downward stepping [4]. thus inclusive analysis on movement of stair gait in a view of gait rehabilitation can be helpful for movement efficiency of lower limb's joint, development of prosthesis and exercise program [5]. Human nerve system enables movement of lower limb to control optimistically in response to weight change on higher stair, but do not yet illuminate on its precise mechanism.

Background which should be considered in pursuit of optimal height for efficiency of human gait is relationship with various situations encountering habitually in real life [6]. That is, stair height was dependent on environment which stair was positioned, because of rather higher in private than that of public house [7].

Alteration of stair height may cause ankle movement to occur dorsiflexion in order of rear foot following forefoot touch-down during touch-down on its leg of each individual but the its strategy may differ to individual [8]. While touch-down of forefoot during downward stepping prevents its instability by reducing kinetic energy of whole body [9], it reduce the gait velocity and consequently requires more energy of lower limb. And then the obtained energy was converted to kinetic energy through partial absorption to rear leg (supporting leg) [10]. In a respect of dynamics, because touch-down of fore foot was positioned in more front of center of pressure than center of gravity, forward rotational momentum in contrast to touch-down of rear foot may be controlled easily [11]. But alteration of stepping strategy during downward stair may greatly give relative contribution to momentum of ankle joint [6], and then may result in instability in position of ankle joint [12].

Nowadays stair gait was regarded as activity of daily life related with carrying of weight in common [3]. But backpacks was used to heighten capacity of loading. That is, human may have difficulty in controlling added weight in addition to body weight during locomotion exercise, and it may occur perturbation to lower limb by reducing both individual's balance and agility [13]. Because increase of impulse force may have close relation with injuries, human alters frequently a downward stepping strategy not to over load owing to hyper flexion of knee joint [6]. Therefore human should interact with dynamics and periodic cycle in a line with added weight to body during locomotion [13].

Like this, analysis on biomechanics and motor control may enhance the level of understanding of various and complex procedure related with exercise [5], but it may be necessary to considerate under conditions of stairs height and weight changes. Therefore it needs properly distributed model on whole body in accordance with alteration of various weights and at the same time quantitative evaluation on characteristics of lower limb for added weight during downward stair.

For solution of this problem, it is necessary to investigate gait strategy combined a whole body modeling of human with gait measurement through 3-dimensional cinematography from stair height which alteration of forefoot touch-down strategy is possible. And then measurement result of gait can be utilized on deciding an effect of unknown factors (stair height of 30 cm, weight changes). Here the first assumption is that stair height of 30 cm may induce forefoot touch-down strategy. The second is that human can alter leg stiffness to receive added weight during downward stair. The third is that experimental conditions of this study may more contribute to increase a vertical reaction force than forward rotation and movement.

2. Experiments

2.1 Subjects

Total adult male subjects (n=10, mean age: 21.80±1.87 yrs, mean heights: 177.58±5.15 cm, mean weights:

76.43±3.15 kg) participated in the experiment. Prior to experiment, details on possibility of normal gait, injury history record on joint of lower limb, surgical operation and treatment were confirmed through questionnaire. Only 20% of body weight was applied in previous study related with carrying weight and stair gait [14], but 30% of body weight in this experiment was loaded in line with necessity of more extensive range of load [1].

2.2 Experimental approach

Standardization of stair (Figure 1) made of wooden box was as follows (rise 0.3 m, tread 0.29 m, width 1 m).

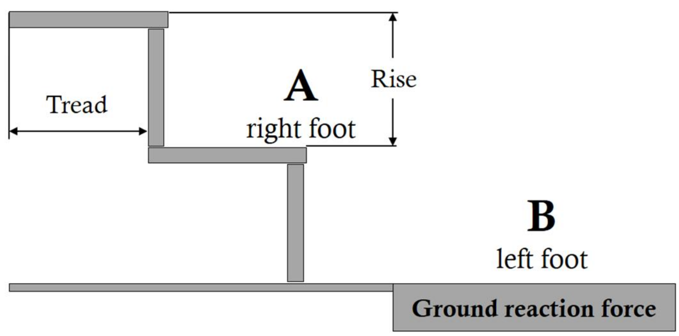

Figure 1. Simple stair geometry

3-Dimensional cinematography was utilized for collection of kinematic data on gait motion carrying an added weight (locomotion from A point to B point). For the collection, force plate (1) (AMTI-OR-7, Advanced Mechanical Technology Inc., Watertown, MA, USA) and motion capture camera (12) (VICON Vantage and Vero, Vicon Motion System Ltd., UK) were installed within indoor lab. Marker position attached on joints of each subject was transferred to the analysis software package through digitization at 100 Hz frequency (Nexus 2, Vicon Motion System Ltd, UK; Kwon 3D XP ver 4.0, Visol, Gwangmyeong, Korea), and data of ground reaction force was collected at 1,000 Hz (Gain: 4 k, Voltage: 5 V). Downward stepping stair was performed with one's preferred velocity, and with repetitive measurement of 10 times with left-foot during supporting phase (Touch-down ~ Toe off). Reflex markers attached on joints for calculation of kinematic data of lower limb and COM of whole body were on head (3 markers), trunk (4 markers), upper extremities (14 markers), and lower extremities (22 markers). Error of kinematic data may be differ according to position of carrying weight during gait [15]. Therefore all subject wore jacket (FROGFITNESS, Weight Vest., China) during carrying weight in order to distribute evenly against anterior-posterior direction of trunk. Each load conditions were no-load, 10%, 20% and 30% of body weight, and measurement order were performed randomly.

2.3 Definition of analysis phase

- In Formula (1), Stiffness of lower limb was calculated with dimensionless, and calculated divided normalized maximal vertical force by change ratio (%) of minimal length of leg [16-18].

$$K_{leg} \frac{Peak\ vertical\ force\ (BW)}{(l_0 - l_{min})l_0} \tag{1}$$

Where peak vertical force is ratio of the ground reaction force normalized to body weight, to the change in leg length during supporting phase with left leg, and normalized to leg length at foot contact, l_0 [16]

where l_{min} is the minimum leg length during supporting phase with left leg, leg length was estimated as the distance from center of pressure [19] to the center of the pelvis [16].

- Resultant velocity on center of gravity was calculated in all direction (X, Y, Z-axis)

- Maximal flexion angle of lower limb joint (hip, knee, and ankle) was calculated during supporting phase of left foot

Hip angle: relative angle between pelvis and thigh on the axis of hip joint center

Knee angle: relative angle between thigh and shank on the axis of knee joint center

Ankle angle: relative angle between shank and foot on the axis of ankle joint center

- Inclined angle of trunk was defined as positive (+) of forward and negative (-) of backward of trunk.

- Rotational torque of whole body, viewed from X- axis (sagittal plane) on relation between center of pressure and center of mass was set up as forward rotation (+) and backward rotation (-) against progressing direction.

Mean±SD on all variables was calculated using statistical package (PASW 21.0 program IBM., Chicago, IL, USA). Repetitive measurement on weight changes (4 conditions) was treated and significant difference was tested on all variables through sphericity test (Mauchly).

3. Results

3.1 Kinetic and leg length

Sphericity test (Mauchly) was satisfied the result of repetitive measurement on all variables relative to weights change (p>.05). Kinetic analysis during downward stepping stair was as Table 1 and Figure 2. Leg stiffness calculated by dimensionless, peak vertical force (PVF) and rotational torque relative to weight change showed significant difference (p<.05).

Table 1. Leg stiffness from downward stepping stair

Variable	No load	10% of BW	20% of BW	30% of BW	*F*	*p-value*
Dimensionless leg stiffness	2.60±0.50	2.75±0.62	3.23±0.64	3.36±0.69	4.814	0.008**
Peak vertical GRF (BW)	2.41±0.45	2.52±0.54	2.97±0.61	3.07±0.58	4.586	0.010*
Leg length (%)	7.26±1.00	7.82±2.35	8.00±2.40	8.13±2.30	0.944	0.433
Torque of whole body (Nm)	39.73±12.73	29.47±13.21	36.12±10.73	40.12±11.35	3.778	0.22*

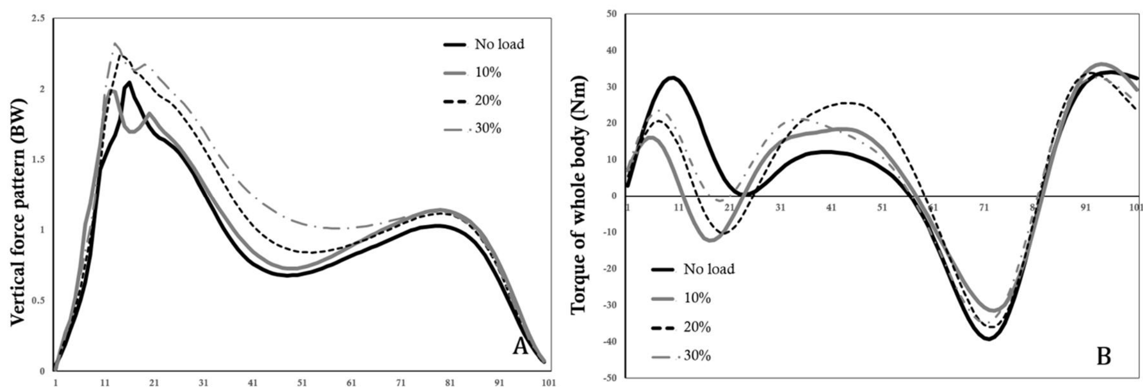

Figure 2. Vertical force (A), torque of whole body (B) patterns during downward stepping stair

Kinematic analysis during downward stepping stair was as Table 2 and Figure 3. Anterior-posterior angle of trunk and maximal angle of hip joint showed significant difference relative to weights change (*p*<.05). At initial touch down, angle of hip and ankle did not show difference.

Table 2. Kinematic variables from downward stepping stair

Variable	No load	10% of BW	20% of BW	30% of BW	*F*	*p-value*
Center of mass position-Z axis (m)	0.94±0.02	0.93±0.02	0.93±0.01	0.92±0.02	2.680	0.067
Center of mass velocity-Y axis (m/sec)	0.80±0.11	0.72±0.10	0.80±0.13	0.80±0.12	1.877	0.157
Front-rear tilt angle of trunk (degree)	-13.06±2.67	-11.69±2.71	-11.71±3.31	-9.44±2.94	9.065	0.001***
Hip flexion angle (degree)	124.12±5.06	119.23±8.08	121.27±5.63	122.94±7.94	3.790	0.022*
Knee flexion angle (degree)	143.86±5.32	139.83±7.11	141.11±5.16	139.13±6.54	1.544	0.226
Ankle flexion angle (degree)	80.25±4.35	80.04±1.04	79.25±5.29	77.24±5.47	1.323	0.287
Initial contact phase						
Hip joint angle (degree)	125.15±4.50	123.03±5.63	124.22±5.38	125.38±3.61	1.100	0.366
Knee joint angle (degree)	168.31±4.68	167.61±5.36	167.98±6.37	167.85±4.35	0.106	0.956
Ankle joint angle (degree)	121.09±10.64	120.01±10.54	122.25±7.97	121.27±7.69	0.139	0.718

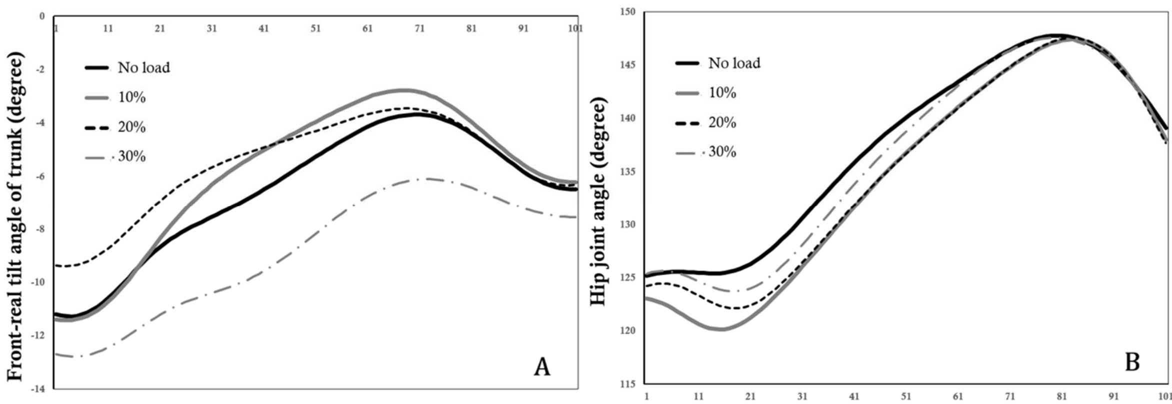

Figure 3. Front-rear tilt angle of trunk (A), hip joint angle (B) patterns during downward stepping stair

4. Discussion

Effect on alteration of carrying weights and stepping strategy of lower limb during downward stepping stair may ultimately contribute to enhanced prevention and development of rehabilitation program for reduction of injury risk. Thus this study investigated an effect of alteration of stepping strategy and change of carrying weights during downward stepping stair.

When stair height was lowered during downward stepping stair, potential energy was diminished, and therefore more kinetic energy obtained increased linear and angular momentum [10]. When floor of house was more lowered, gait was performed easily, but kinetic energy obtained by eccentric contraction during touch down of leg should be absorbed in case of higher floor [20]. Thus all subject's ankle angle viewed from anatomical position prior to downward stepping stair was range within 101.62±2.92 degree. And ankle joint showed forefoot touch down pattern at initial touch down during downward stepping from 30cm height. All subject's ankle angle showed range within 121.09±10.64 degree and more dorsiflexion pattern than static position. Thus this result satisfied the first assumption of the study. Therefore this result supported that kinetic energy obtained at initial stage of downward stepping stair may absorb easily when touching down with toe [20].

Forefoot touch down strategy during downward stepping stair may reduce both vertical and horizontal velocity and thus impulse force [20]. Weights alteration did not influence on velocity change of center of gravity in result of both previous and this study in common. Also any minimal change of vertical height of center of mass in supporting phase did not show, which may be due to forefoot touch down strategy and angle pattern of lower limb (knee, ankle).

But result of this study was differ to assertion that change ratio (%) of leg length during running with 30% weight of body weight was controlled within shorter range of length and thus added weight was absorbed in crouch posture [16]. Thus this study did not show any symptom on change (joint angle, center of mass) of lower limb's length during downward stepping stair relative to added weight. While maximal vertical ground reaction force normalized by body weight and dimensionless stiffness of leg showed more increasing pattern relative to increase of weight. Thus leg stiffness had linear relationship between strain of body and force applied [21].

Because a certain level of stiffness for optimal performance is essential, the enough resistant force is necessary to generate controlled movement when larger external force was applied on body [21]. Level of stiffness differed from relative to activity intensity generally, but in this study, level of leg stiffness showed increasing pattern relative to weight increase when compared with condition of no-load.

Therefore forefoot touch down strategy maintained optimal level of stiffness (dimensionless value 2.60)and level of reduction of impulse force [20] during downward stepping stair under no-load but altered it in case of added weight. Therefore the second assumption was satisfied in that all subject took more rigid posture of lower limb relative to increase by each 10%, 20%, and 30% of body weight and absorbed added weight successfully.

Angle of hip joint showed most extended pattern under no-load, which more and more extended according to increase of added weight after showing most flexed pattern in 10 % weight of body weight. This pattern supported an assertion (in rotational torque of whole body, inclined angle of trunk) that rather more rigidity between trunk and thigh than leg length may be increased. Rotational torque showed backward inclined angle of trunk of -13.06 ± 2.67 degree in case of 39.73 ± 12.73 Nm of under no-load, but torque showed similar value of 40.12 ± 11.35 Nm under 30% weight of body weight and inclined angle of trunk showed close position to vertical line of -9.44 ± 2.94 degree.

Therefore there was no problem in controlling an impulse force (ground reaction force, leg stiffness), maintenance of kinetic energy (optimal generation of rotational torque) and posture control (inclined angle) by forefoot touch down strategy under no-load. But this strategy suggested possibility that might have difficulty in controlling ability of posture under 20% and 30% of added weight after having gradual change under 10% of body weight.

Consequently experimental conditions (weight change) of this study had more influenced on vertical ground reaction force than forward rotation of whole body and controlling of joint movement of lower limb during downward stepping stair, which satisfied the third assumption of this study. Therefore added weight not only influenced on forward rotational torque of body, but also had close relationship between impulse force to vertical direction and increase of stiffness of body during downward stepping from high stair. Optimal range of stiffness which can not only maximize the performance but also minimize an injury risk may exist [21]. Therefore further study considering variables of carrying position of weight, gender and stair height etc., may provide useful information for occupational field, layperson, and those who require exercise rehabilitation.

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