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QUANTITATIVE ANALYSIS OF GAIT PATTERN AND ELAPSED SUPPORTING-TIME RELATIVE TO HEIGHTS OF THE STAIRS AND SHOE HEEL DURING ASCENDING ONTO A LARGE-SIZED BUS

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Abstract

The aim of this study is to analyze quantitatively the variation of elapsed supporting-time, horizontal velocity of the center of gravity (COG) and angle of the lower extremities during ascent of both bus-stairs and normal stairs depending whether to wear high heeled shoes. The method of three-dimensional cinematography is employed for motion analysis. The results show that wearing high heeled shoes during ascending the bus-stairs of the higher height structure influences to delay of the elapsed supporting-time and reduction of COG velocity even for healthy adult women who perform normal gait.

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As we observe the statistical significance of interaction effect at the angle of the knee and ankle joint, wearing high heeled shoes increases an upward displacement of COG and a forward displacement of the supporting leg, therefore, pushing-up of the pre-supporting foot is not performed easily. Finally, the other leg performs a role in supporting the body weight to ensure dynamic stability and to avoid the posture instability caused by wearing high heeled shoes.

1. Introduction

The elaborated system of transport and traffic network has been an issue due to urbanization. It has shown the trend that a growing number of people are using public transportations (subway, city bus, express bus, train, etc.) rather than private vehicles for local or long distance travels due to better accessibility and convenience. The use of public buses large-sized has been concentrated, but many passengers have experienced discomfort when ascending the higher bus-stairs than the normal stairs [19] and suffered frequent delays of bus arrival time [11].

From the point of view of bus passengers, the motion of stair climbing requires more stability and capability which support the body weight to raise the body at the supporting phase and the opposite leg performing the function at the swing phase keeps a flexed posture followed by a forward progression [18]. Also, because of ascending motion being performed by the range of motion (ROM) of the joint [16] and then having increase of flexion angle and moment of knee [2, 8], it requires more muscle strength of leg to raise the center of gravity (COG) of the body upward [12].

From the point of view of public transport drivers, the scheduled interval on bus arrival and frictions with passengers increase stress on the driver, which may cause traffic accidents [13]. Since safe driving is entirely determined by the judgment and responsibility of the bus driver, a high level of tension and concentration is expected for the driver who feels extreme anxiety about traffic accidents [9]. That is, uncertainty in bus arrival time is an important factor giving a large stress to the bus driver as well as giving a discomfort to passengers.

Although various factors affect the estimate of bus arrival time due to the time delay in getting on and off at a bus stop, it mainly depends on how many passengers get on and off, specifically whether young students less developed in physical ability and the old and the infirm deteriorated in physical ability get on and off [11]. In addition to young students and the old and the infirm, young adult women wearing high heeled shoes may experience discomfort and suffer disability during ascending the bus-stairs. Most people wear shoes to reduce the impact force exerted on the body during walking and to prevent the various injuries of the lower extremities' joint on the human body [4], but women-wear high heeled shoes can cause the instability of the ankle joint by the center of pressure (COP) abnormally cumulated on calcaneus and talus of foot [5]. After all, it may induce decrease of locomotion velocity of COG and high risk of falling with increase of impact force at heel strike [3, 23]. When considering the fact that the female tendency preferring high heels shows no exception even on the buses [7], the interaction of increasing the stair and heel height may give rise to delay of the time elapsed during ascending and descending and more difficulties in gait motion [6].

To reduce inconvenience of passengers and delay of bus arrival time during ascending and descending and to ensure the safe manipulation of bus drivers, the adoption of low floor (non-step) buses must be made extensively and quickly, however, it is in conjunction with problems of budget, maintenance, short rotational radius and slope road driving, etc.

This study is focused on the investigation of the variances of elapsed time, horizontal velocity of COG and angle of the lower extremities during ascent of both bus-stairs and normal stairs depending on whether to wear high heeled shoes.

2. Method

Subjects participated in the experiment are composed of 10 female adults (age: 23.00±1.41yrs, height: 165.94±3.34cm, body weight: 57.33±3.15kg, $n = 10$) who are free of any muscular-skeletal dysfunction of the lower extremities. In advance of the experiment, all subjects were informed on the details of the aim and procedure of the study and gave their consent for voluntarily participation.

Considering indoor experimental environments, experimental stairs were made of wooden-boxes to set the height of 18cm for the normal stairs [24] and the height of 37.66cm for the bus-stairs [19]. The experimental set-up for three-dimensional cinematography consists of a control box, four cameras (HDRHC7/HDV 1080i, SONY) and lighting facilities. The control box is of the 3D spatial frame of $2\text{m} \times 2\text{m} \times 1\text{m}$ and contains thirty-six control points corresponding to the spatial real coordinates. A four-camera system allowed the kinematic measurement of the body, recording data at a speed of 60frames/sec with an exposure time of $1/500\,\text{sec}$. Prior to data acquisition, subjects practiced both of the stairs several times until they became used to the motion. All participants wore high heeled shoes of the 9cm height after rehearsal gait. In this paper, the heights of shoe heel are distinguished by 9cm and 0cm.

The body segment parameters [17] are utilized to compute COG of the body segment and whole body of the individual subjects. Thirty-one retro-reflective markers are attached to the body including twenty-one body joints and thirty others: right•left toe, right•left heel, right•left/lateral•medial malleolus, right•left shank, right•left/lateral•medial epicondyle, right•left thigh, right•left anterior superior iliac spine, sacrum, right•left/lateral•medial wrist, right•left/lateral•medial elbow, right•left shoulder, chin and nose.

Stair ascent is started in front of the stairs on ground level. To maintain the steady state of ascending velocity, subjects were asked to climb three stair-steps. During ascent, a gait cycle was defined starting with foot touch-down on the first step and ending at the next foot touch-down on the second step. Foot touch-down always occurred with the same foot among all subjects. All participants preferred right foot from the initial foot touch-down, putting left foot on ground level during ascending the stairs. In order to minimize error in the data collected, horizontal displacement between bilateral foot touch-down and forward velocity of COG was not restricted.

The analysis phase was defined to be from the initial touch-down of right foot on the first step to the heel take-off of the same foot. We define *Y*-axis in the direction of ascending the stairs, *X*-axis in the lateral direction of *Y*-axis and *Z*-axis perpendicular to *X*-*Y* axes. See Figure 1.

The analysis phase is defined as the supporting phase which is the interval from the initial touch-down of right foot on the first step to the heel take-off of the same foot. Events are composed of IC and TTO defined as follows:

Event 1. IC (initial contact): Contact of right foot on the first step.

Event 2. TTO (toe take off): Take-off of right foot on the first step.

Four relative angles of segments are analyzed during the supporting phase from the initial touch-down of right foot on the first step to heel take-off of the same foot. We define the angles of segments as the following:

θ^1 : hip joint angle : relative angle between trunk and thigh segment,

θ^2 : knee joint angle : relative angle between thigh and shank segment,

θ^3 : ankle joint angle : relative angle between shank and foot segment,

θ^4 : front-rear angle of trunk : range of motion (ROM) in forward-backward direction of trunk from sagittal plane.

According to heights of the stairs and shoe heel, kinematic variables are calculated by using the program of Kwon 3D XP ver.4.0 (2007, Visol, Korea). The direct linear transformation method [1] is employed to transform the three-dimensional Cartesian coordinates of control points and body segment points, and synchronizes the two-pair coordinates. The raw data digitized are filtered by the Butterworth’s low pass filtering method to remove the noise out of the 6Hz frequency. All the variables analyzed in the study are tested statistically by the two-way analysis of variance. When significant differences are found, the post-hoc test (Duncan) is conducted for validation. A p value less than 0.05 is considered to be significant statistically.

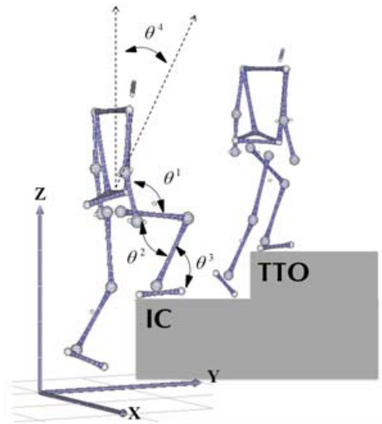

Figure 1. Experiment field.

3. Results

According to heights of the shoe heel and stairs, the elapsed supporting-time is summarized in Table 1. The result indicates more delayed time during ascending the bus-stairs than the normal stairs and shows significant differences statistically $(p < .001)$. But no significant differences $(p > .05)$ are statistically shown neither in wearing high heeled shoes nor in interaction effect $(p > .05)$.

During the supporting phase, the mean velocity of COG becomes slower when wearing heeled shoes of the height 9cm than flat shoes of the height 0cm $(p < .05)$ and during ascending the bus-stairs than during ascending the normal stairs $(p < .001)$, whereas interaction effect is shown to have no significant differences in the velocity of the center of body mass (COM) $(p > .05)$. See Table 2.

As a result of the analysis of the inclined angle θ^4 in sagittal plane of trunk for each event relative to heights of the stairs and shoe heel in Table 3, it shows significant differences in the angle which was more tilted forward at both event of IC and TTO when wearing the heeled shoes of the 9cm height than the flat shoes of the 0cm height $(p < .001)$. At the IC event, the inclined angle in sagittal plane of trunk shows no dependency on neither heights of the stairs $(p > .05)$ nor the effect of interaction $(p > .05)$. In contrast, at the TTO event, considerable differences are found in the angle with the posture more tilted forward during ascending the bus-stairs than the normal stairs $(p < .05)$. The interaction effect observed at the TTO event was tested by the one-way analysis of variance. It verifies that the front-rear trunk angle is influenced more by wearing high heeled shoes than by the height of the stairs at the TTO event.

In Table 4, the segment angles of the lower extremities are analyzed for each event of IC and TTO. First, at the IC event, the hip joint angle θ^1 achieves a higher degree of flexion relative to increasing heights of the stairs and shoe heel, which exhibits significant differences statistically $(p < .001)$. In contrast, at the TTO event, the hip joint angle shows a higher degree of extension relative to increase of the heel height, which results in considerable differences $(p < .001)$. However, there is no significant dependency on the stair height at the TTO event $(p > .05)$. The effect of interaction is not observed at both events of IC and TTO $(p > .05)$.

At the IC event, the knee joint angle θ^2 represents statistically significant differences, showing a more flexed pattern relative to increasing heights of the stairs and shoe heel $(p < .1)$, whereas at the TTO event, it represents significant differences showing a more extended pattern relative to increase of the heel height $(p < .001)$. There is no significant dependency on the stair height at the TTO event. The interaction effect is observed not at the IC event but at the TTO event. Specifically, the one-way analysis of variance verifies that high heeled shoes rather than the stair height affect the knee joint angle at the TTO event $(F = 95.120,\ p < .001)$.

At the IC event, the ankle joint angle θ^3 exhibits a higher degree of plantar flexion relative to increasing heights of the stairs and shoe heel presents significant differences $(p < .01)$. In contrast, at the TTO event, the ankle joint angle obtains a higher degree of dorsiflexion relative to increase of the heel height $(p < .001)$, but does not show dependency on the stair height $(p > .05)$. The interaction effect is statistically significant not at the IC event but at the TTO event. It is verified to be more influenced by high heeled shoes than by the stair height $(F = 3.258,\ p < .05)$.

Table 1. Result of elapsed supporting-time relative to heights of shoe heel and stairs during ascending (unit: sec)

Section	Heel height (*H*)	Stair height (*S*)		Total average	Source	*F*	*p*
		18cm	37.66cm				
Supporting time	0cm	0.758 ± 0.08	0.921 ± 0.06	0.839 ± 0.11	Heel	.027	.870
	9cm	0.783 ± 0.04	0.903 ± 0.53	0.843 ± 0.07	Stair	48.443	.001***
	Total average	0.770 ± 0.06	0.912 ± 0.05	0.841 ± 0.09	$H \times S$	1.153	.290

Note: *** $p < .001$, Heel: heel height of the main effect, Stair: stair height of the main effect, $H \times S$: interaction

Table 2. Result of COM velocity relative to heights of shoe heel and stairs during ascending (unit: m/sec)

Section	Heel height (*H*)	Stair height (*S*)		Total average	Source	*F*	*p*
		18cm	37.66cm				
COM velocity	0cm	72.39 ± 4.44	63.13 ± 6.55	67.76 ± 7.22	Heel	4.319	.045*
	9cm	67.88 ± 3.62	60.78 ± 3.75	64.33 ± 5.92	Stair	24.606	.001***
	Total average	70.14 ± 4.57	61.96 ± 6.11	66.05 ± 6.75	$H \times S$	.431	.516

Note: *** $p < .001$, * $p < .05$, Heel: heel height of the main effect, Stair: stair height of the main effect, $H \times S$: interaction

Table 3. Result of front-rear angle relative to heights of shoe heel and stairs during ascending (unit: degree)

Section	Heel height (*H*)	Stair height (*S*)		Total average	Source	*F*	*P*
		18cm	37.66cm				
IC	0cm	5.67 ± 2.63	4.02 ± 2.23	4.85 ± 2.55	Heel	39.056	.001***
	9cm	7.95 ± 1.72	8.16 ± 2.50	8.05 ± 2.12	Stair	1.944	.167
	Total average	6.81 ± 2.48	6.09 ± 3.14	6.45 ± 2.83	$H \times S$	3.281	.074
TTO	0cm	8.10 ± 2.76	7.08 ± 2.46	7.59 ± 2.63	Heel	17.755	.001***
	9cm	8.28 ± 4.07	12.23 ± 1.33	10.26 ± 3.60	Stair	5.370	.023*
	Total average	8.19 ± 3.43	9.66 ± 3.26	8.92 ± 3.41	$H \times S$	5.432	.022*

Note: *** $p < .001$, * $p < .05$, Heel: heel height of the main effect, Stair: stair height of the main effect, $H \times S$: interaction

Table 4. Result of joint angles relative to heights of shoe heel and stairs during ascending (unit: degree)

Section		Heel height (H)	Stair height (S)		Total average	Source	F	p
			18cm	37.66cm				
R Hip θ^1	IC	0cm	118.69 ± 7.05	92.09 ± 4.79	105.39 ± 14.72	Heel	26.856	.001***
		9cm	107.63 ± 8.90	87.11 ± 6.30	97.37 ± 12.88	Stair	231837	.001***
		Total average	113.16 ± 9.70	89.60 ± 6.07	101.38 ± 14.33	$H \times S$	3.858	.053
	TTO	0cm	162.02 ± 5.20	161.40 ± 4.42	161.71 ± 4.78	Heel	23.597	.001***
		9cm	166.10 ± 2.47	166.04 ± 3.40	166.07 ± 2.94	Stair	.141	.709
		Total average	164.06 ± 4.52	163.72 ± 4.55	163.89 ± 4.51	$H \times S$	.096	.758
R Knee θ^2	IC	0cm	106.73 ± 4.97	83.40 ± 6.64	95.07 ± 13.16	Heel	8.824	.004**
		9cm	100.61 ± 6.44	81.99 ± 4.28	91.30 ± 10.86	Stair	273.757	.001***
		Total average	103.67 ± 6.47	82.70 ± 5.56	93.18 ± 12.14	$H \times S$	3.471	.066
	TTO	0cm	157.90 ± 13.12	161.84 ± 6.21	159.87 ± 10.33	Heel	12.077	.001***
		9cm	167.81 ± 2.72	164.14 ± 5.36	165.97 ± 4.59	Stair	.006	.937
		Total average	162.85 ± 10.62	162.99 ± 5.84	162.92 ± 8.51	$H \times S$	4.694	.033*
R Ankle θ^3	IC	0cm	88.12 ± 6.11	91.44 ± 6.83	89.78 ± 6.61	Heel	276.440	.001***
		9cm	110.54 ± 4.45	115.41 ± 7.20	112.98 ± 6.40	Stair	8.615	.004**
		Total average	99.33 ± 12.52	103.42 ± 13.97	101.38 ± 13.34	$H \times S$	.036	.582
	TTO	0cm	126.01 ± 6.64	130.90 ± 9.50	128.45 ± 8.46	Heel	4.299	.042*
		9cm	126.51 ± 5.35	122.41 ± 11.57	124.46 ± 9.14	Stair	.042	.837
		Total average	126.26 ± 5.96	126.66 ± 11.30	126.46 ± 8.98	$H \times S$	5.432	.022*

Note: *** $p < .001$, ** $p < .1$, * $p < .05$, Heel: heel height of the main effect, Stair: stair height of the main effect, $H \times S$: interaction

4. Discussion

The city's public transportation system has been an important issue as an alternative to resolve traffic congestion. Specifically the public bus services have played a critical role with universal use. Thus it is necessary to enhance reliability and accuracy in the estimate of bus arrival time. Moreover, the design of the bus-stairs used to get on and off has to be improved to avoid discomfort of passengers. But there are many difficulties in solving the problems thoroughly. Furthermore, in case of female wearing high heeled shoes among bus passengers, the abnormality of hyper-plantar flexion of foot is appeared in the ankle joint due to structural characteristics of the high heeled shoes [6]. The forward locomotion of COG requires the harmonious control and power generation of ankle and foot [14, 15], but high heeled shoes can cause an abnormal gait posture, resulting in possible delay of the boarding time elapsed during ascending onto a bus. Based on these problems, this study has analyzed the kinematic variables relative to heights of the stairs and shoe heel.

During ascending the stairs, the elapsed supporting-time of right foot at the first stair step does not show significant dependency on whether to wear high heeled shoes. However, it exhibits more delayed characteristics during ascending the bus-stairs than during ascending the normal stairs. As a result of the analysis of the ascending motion of 0cm, the supporting time elapsed during ascending the bus-stairs delays by 21.5% compared to that during ascending the normal stairs. Because the supporting phase of the opposite foot during ascending the stairs is essential in the maintenance of stability to move COG of the body in an upward direction [18], the bus-stairs higher than the normal stairs necessitates more supporting-time elapsed for the locomotion of COG.

The gait velocity of a forward displacement of COG shows significant differences relative to stair heights depending on whether to wear high heeled shoes. Based on the percentage on analysis of time variation using main effect, the motion of bus-stair ascent displaces more slowly by 11.66% compared to that of normal stairs. When wearing high heeled shoes, the gait velocity during ascending normal stairs is slower by 5.06% compared to that when wearing flat shoes of the 0cm height. Hyun [6] reported the velocity of 68.43±5.06cm/sec and 67.22±7.66cm/sec during ascent of the normal stairs when wearing 0cm high flat and 9cm high heeled shoes, respectively. Our results partially consist with the previous studies that the velocity of stair ascent becomes slower rather than that of stair descent and level walking. These can be interpreted as a consequence that the bus-stair height is a matter of standards higher than the normal stair height, and therefore, the functional feature that wearing high heeled shoes reduces dynamic stability and balance during level walking [20-22] is appeared even during ascending the stairs.

During stair ascent, an upward displacement of COG requires forward inclination of trunk in sagittal plane and support of the body weight occurred on the other foot [14] which gives help to the posture control of COG.

The forward inclination of trunk is not shown significantly during bilateral supporting phase after supporting of right foot [14]. In this study, at the IC event, no considerable variation is exhibited relative to the heights of the stairs, but the TTO event shows the trunk more tilted forward during ascending the bus-stairs and achieved increase of 17.94% based on the analysis of main effect of trunk Inclination. That is, increase of stair heights was considered to be in a close relation in proportion to the forward inclination angle of the trunk for stability maintenance and propulsion during locomotion of COG in a forward-upward direction. However, the functional feature of trunk inclination contributes to increase of energy expenditure following stabilization of the knee joint with mobilization of the hip joint and trunk extensors [16]. Therefore, in further study, it is necessary to analyze relations among variables including EMG and kinematic and kinetic variables on the mechanism.

At the IC event, forward inclination angle of trunk represents a more tilted pattern and increases 65.97% according to wearing high heeled shoes. This can be interpreted as a sign for a forward progression and pre-posture control of the opposite leg during the supporting phase of one leg since the structure of high heeled shoes reduced stability leading to more plantar flexion of the ankle joint angle. Specifically, even at the TTO event followed the IC event, wearing high heeled shoes increases the forward inclination angle of trunk by 35.17% and shows the interaction effect in which wearing high heeled shoes rather than stair heights is more influenced in the inclination angle of trunk. Nahorniak et al. [14] ascertained movement to retain the control of COG and maintenance of stability at the TTO event defined that both the take-off of right foot and the supporting phase of left foot occur simultaneously.

Since the structural shape of high heeled shoes together with increase of the heel height is a critical factor of the interaction effect in the trunk inclination, it has a close relation with the angle change of the low extremities [16]. As observed in our analysis of the angle change of the low extremities, wearing high heeled shoes induces more flexion of the hip and knee joint and more plantar flexion of the ankle joint at the IC event and the ratio of angle change showed 5.40%, 3.96% and 25.84%, respectively. Regardless of imbalance of muscles and injury of the knee joint, the structural shape of shoes alone affects the knee joint stability, for which a flexed pattern of the knee joint needs the higher level of muscular activation [10]. The angle change of the low extremities analyzed in this study demands more muscle strength and movement during ascending the bus-stairs higher than the normal stairs. The percentage analysis of the angle change indicates 20.82% in the hip joint, 20.22% in the knee joint and 4.11% in the ankle joint.

The TTO event which means the moment of concurrence of left foot touch-down and right foot take-off, followed the supporting phase of right foot is the starting point of transferring the body weight to left foot. For this reason, the change of angle in the lower extremities does not show significant differences relative to stair heights. In contrast to the IC event, at the TTO event, wearing of high heeled shoes causes more extension of the hip and knee joint, and also more plantar flexion of the ankle joint compared to wearing 0cm flat shoes. The change ratio shows 7.60% in the hip joint, 3.96% in the knee joint and 25.84% in the ankle joint, which is determined as a consequence that the opposite leg performs fast a role in supporting the body weight to ensure dynamic stability and to avoid the posture instability caused by wearing high heeled shoes. As we observe the interaction effect at the angle of the knee and ankle joint, wearing high heeled shoes increases an upward displacement of COG and a forward displacement of the supporting leg, therefore, pushing-up of the pre-supporting foot is not performed easily.

Summarizing all the analyses in the present study, it verifies that wearing high heeled shoes during ascending the bus-stairs of the higher height structure influences to delay of the elapsed supporting-time and reduction of COG velocity even for healthy adult women who perform normal gait. Since more of strength and displacement is required in the supporting leg and pushing-up of the opposite leg is not performed consistently at the IC event, this feature implies a possibility that the less-developed young students and the weaken elderly people in muscular strength may cause more delay of the elapsed time during bus-stair ascent or fail to achieve stair ascent.

5. Conclusion

The present study analyzed and acquired quantitative data of gait pattern relative to stair heights depending on whether to wear high heeled shoes during ascending the stairs for young adult women. The supporting time elapsed during ascending the bus-stairs represented more delayed than that of the normal stairs. The COG velocity exhibited a decreasing tendency with increasing heights of the stairs and shoe heel. The inclination angle of trunk showed more flexed forward at the IC event when wearing high heeled shoes and also increased forward flexion with increasing heights of the stairs and shoe heel at the TTO event. Angle change of the lower extremities at the IC event showed a more displaced pattern relative to increase of stair height. In contrast, at the TTO event, wearing high heeled shoes made pushing-up functions for lifting the body to be worse than that when wearing flat shoes of the 0cm height. Since extensive adoption of low floor (non-step) buses has too many difficulties to be made quickly, analyzing the time elapsed during ascending onto a large-sized bus is a valuable research necessary to relive the discomfort of passengers.

Since the bus-stair is composed of only three steps, the delay in the time elapsed during ascending the stair-steps might be regarded so small to affect the bus arrival schedule. Nevertheless, a growing number of bus passengers can give rise to erroneous estimates of bus arrival time due to the cumulative delay. On the basis of the present work, further study needs to be conducted taking into account various variables including age, sex, use of ascending subsidiaries, and weight of carrying bags.

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