A STUDY OF LOADS ON THE HUMANBODY DURING MOVEMENT ON RAMPS AND STAIRWAYS

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Abstract

The purpose of this study was to reveal the effect of basic conditions of ramps and stairways such as the inclination and dimension of steps on muscle loads and leg joint angles considered as indices of human body loads during ascent and descent. As a result, the effects of changes in the ramp inclination and cross-section forms of stairways on muscle loads and leg joint angles were quantitatively revealed and were organized as basic data used for designs for ramps and stairways.

Keywords: ramp, stairway, inclination, electromyogram, muscle load, leg joint angle

1. THE PURPOSE OF THE STUDY

Previously, a number of human engineering studies have been conducted regarding relationships among ascent and descent motion, and the inclination and dimensions of tread and rise on slopes and stairways. [1)2)3)4)5)6)] Nevertheless, the effect of basic form conditions of slopes and stairways on fundamental indices of human engineering has not been fully understood although this is one of the very basic topics among these previous studies. Due to the lack of in-formation regarding this issue, dimension of steps the present study was conducted this time.

In this study, first of all, muscle loads and leg joint angles are measured during ramp walking to quantitatively grasp the effect of changes in ramp inclinations on these two indices. Second, setting the stairway inclination and 2R + T(R: rise, T: tread, 2R + T: dimension of steps, so named in this paper) as parameters, quantitative data of the two indices during ascent and descent motion on the stairways modeled on their several possible cross-section forms are measured to analyze the effect of changes in cross-section forms of stairways. Using the aforementioned data, characteristics of loads on the human body on ramps and stairways are serially compared.

2. EXPERIMENTAL METHODS

2.1 Experiment devices and used equipments

(1) Ramp: A non-step angle adjustable sloped deck was used (Fig1). Each inclination of the ramp was presented on Figure 1.

(2) Stairway: A serially adjustable inclination and dimension of steps was used as a device realizing 12 different patterns of stairways (Fig2) presented on Figure 2. However, since it was impossible to reproduce three of these patterns (1-A, 1-D, 3-D), wooden stairways (Fig3) were fabricated.

In these experiments, a long vinyl chloride sheet was placed on the surfaces of the ramp and stairways for the prevention of slipping from a safety standpoint. Trias system (DKH Inc., Tokyo, Japan) and Frame-DIAS (DKH Inc.) were used for measurement and data analysis of electromyogram and leg joint angles, respectively.

Fig. 1 Angle adjustable sloped deck

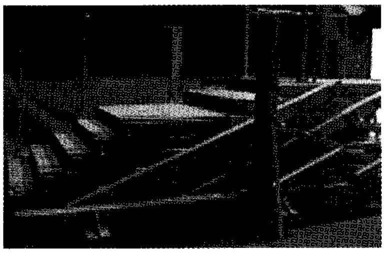

Fig. 2 Adjustable inclination and dimension stairway

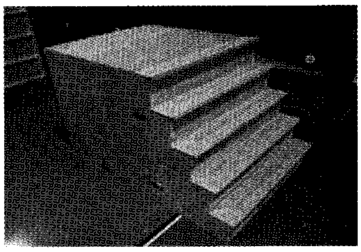

Fig. 3 Wooden stairways

2.2. Subjects

Three university students participated in this study.

2.3. Experimental protocol

(1) Ramp: Maintaining a speed at 4 km/hour (0.59 seconds/footstep) considered as average walking speed of Japa-nese people, the subjects were asked to walk beginning with their right leg with the starting signal and stop on step 6 with placing the left leg in line with the right leg. The horizontal stride length was set to 600 mm for approximation to a natural walking stride and comparison with steps. Specifically, the stride on the slope was adjusted to a length corresponding to approximately 600 mm of the stairway dimension on each slope supposing that the slope was a stairway. The subjects were instructed to avoid unnecessary movement by having them thoroughly confirm the inclination and stride length before measurement.

Table. 1 List of target ramp inclinations in this study

inclination	level	1/15	1/12	1/10	1/8	1/6
angle[°]	0.0	3.8	4.8	5.7	7.1	9.5
R[mm]	0	35	43	50	60	75
T[mm]	600	525	516	500	480	450
2R + T[mm]	600	595	602	600	600	600
stride length[mm]	600	526	518	502	484	456

(2) Stairway: Maintaining stepping with 1.5 Hz step frequency (0.67/step), the subjects were asked to step forward with the right leg with the starting signal and stop by placing the both legs side by side on step 5. In addition, the subjects were instructed to avoid unnecessary strain by having them confirm the inclination and stride length before measurement.

Table. 2 List of target stairways in this study

2R + T \ inclination		A: slowly (26.5°)	B: generally1 (35.0°)	C: generally2 (45.0°)	D: swiftly (56.0°)
1. narrow stride length 2R + T = 450	angle[°]	110	130	150	170
	R[mm]	230	190	150	110
	T[mm]	25.6	34.4	45.0	57.1
	2R + T[mm]	450	450	450	450
2. natural stride length 2R + T = 600	angle[°]	150	180	200	230
	R[mm]	300	250	200	150
	T[mm]	26.6	35.8	45.0	56.9
	2R + T[mm]	600	610	600	610
3. wide stride length 2R + T = 750	angle[°]	190	220	250	280
	R[mm]	370	310	250	280
	T[mm]	27.2	35.4	45.0	55.8
	2R + T[mm]	750	750	750	750

(3) Measurementusing a surface electromyograph: Sensors for surface electro-myography were attached to a total of 8 places (Fig4), the bilateral rectus femoris muscles, biceps femoris muscles, tibialis anterior muscles and gastrocnemius muscles. Measurement by electromyography had been conducted for 4 seconds after the tarting signal and waveform data presented (Fig5) as a figure was ob-tained. The analysis was conducted from step 3 to 5 eliminating the initial movement and the side by side placement of the legs at last. Referring elec-tromyogram data and simultaneously recorded movies, the maximum electromyogram and integrated electromyogram values were extracted.

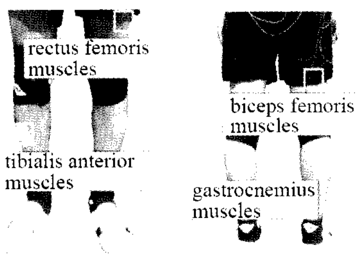

Fig. 4Measurement points of electromyogram

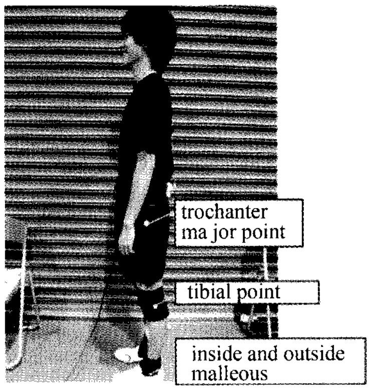

Fig. 5 Measurement points of leg joint angles

(4) Measurement of leg joint angles: Reflectors for observation were attached to the trochanter major

point, bilateral knees and heels as observation points (Fig6). Their leg joint angles were measured by chasing coordinates of observation points from movie data recording their walking from the side of the slope. An angle made by the bilateral tibial points and the trochanter major point as a pivot point was de-fined as a femoral angle. On the other hand, a knee rotation angle was de-fined as follows: the angle obtained by subtracting the angle made by the trochanter major point, the lowest point of the inside and outside malleolus and the tibial point as a pivot point from 180° (Fig7).

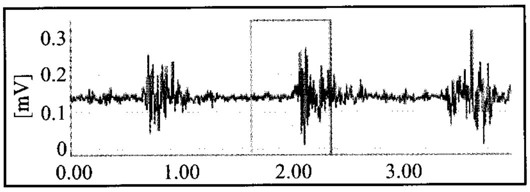

Fig. 6Waveform electromyogram data

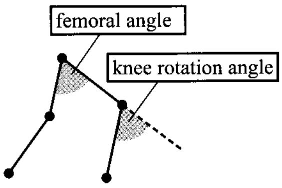

Fig. 7 Definition of measurement angles

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Relationships between the ramp inclination and muscle loads

(1) Regarding the maximum electromyogram values

Outlier detection was performed at the significance level of 0.05 on measurement of the maximum electromyogram values. However, an apparent tendency was not found since dispersion of the data was observed even at the testing of the same subject on the same ramp. The standard deviation obtained after standardizing measurements from each subject and subject muscle by their mean values was about 27%. Therefore, the maximum electromyogram values should be considered to have that level of dispersion in general.

(2) Regarding the integrated electromyogram values per walking cycle

After comparing the extracted integrated electromyogram values per walking cycle (2 steps including stance and swing phases), relatively constant values during both ascent and descent were obtained as a common tendency among all subjects regardless of the ramp inclination (Figure 8: bar graph). Additionally, the standard deviation was ap-proximately 5% after standardizing measurement values of the integrated electromyogram among the subjects in the same manner as the maximum electromyogram values.

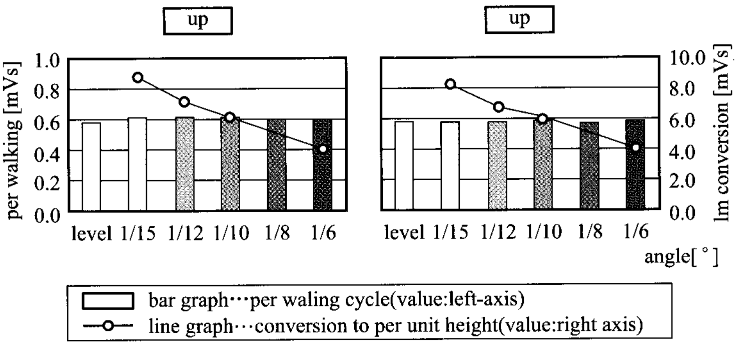

Fig. 8 The integrated electromyogram values depending on the ramp inclinations

(3) Regarding the integrated electromyogram values after conversion to per unit height

Using the integrated electromyogram values per walking cycle and deemed R, the integrated electromyogram values were converted to the values of each one meter ascent and descent.

After comparing these converted integrated electromyogram values on each inclination, it was found that the values decreased when the inclination became steep during both ascent and descent (Figure 8: line graph). The main rea-son for this result is considered that the fewer number of footsteps were needed to reach the unit height on the steep inclination than the gradual inclination.

3.2. Relationships between the ramp inclination and leg joint angles

(1) Regarding the femoral angles

As a common tendency among all subjects, it was found that the maximum femoral angles slightly increased when the ramp inclination was increased during ascent; however, in the case of descent, the angles significantly decreased by increase of the ramp inclination (Fig9). Characteristics in walking during ascent and descent were greatly different. Specifically, regarding changes in the femoral angles during ascent, the both effects of increase due to the rise of swing legs by deemed R and decrease due to the decreased stride length counteracted each other.

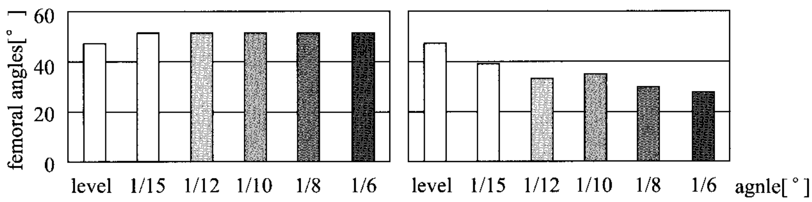

Fig. 9 The maximum femoral angles depending on the ramp inclinations

(2) Regarding the knee rotation angles

Significant changes of the maximum knee rotation angles by variations of the ramp inclination during both ascent and descent were not found presenting constant values (Fig10). Increase of the amount of knee rotation by rise of the inclination was predicted especially during ascent; nevertheless, it was counteracted by decrease of stride length. In addition, the standard deviation of the leg joint angles was approximately 7% after standardizing the measurement values among each subject in the same manner as the electromyogram measurements.

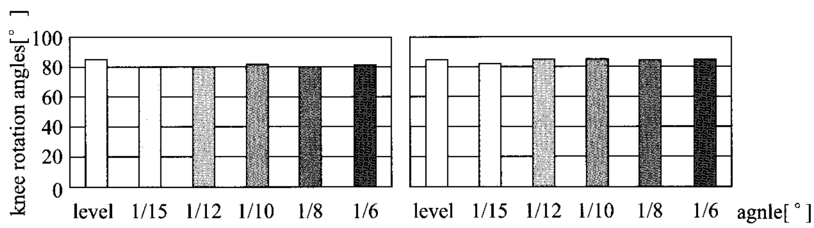

Fig. 10 The maximum knee rotation angles depending on the ramp inclinations

3.3. Relationships among the inclination and dimension of steps, and muscle loads

(1) Regardin g the maximum electromyogram values

One hundred Hz, asampling wavelength gained the stable maximum electromyogram values in our pilot study were adopted in this testing. However, since dispersion of values was observed even on the same subject on each test in a series of motions in the present study, the evaluation using the integrated electromyogram values was added in the following sections.

(2) Regarding the integrated electromyogram values per walking cycle

After comparing the integrated electromyogram values depending on the inclination and dimension of steps per walking cycle (2 steps including stance and swing phases) during ascent and descent, the following results were ob-tained as expected. During ascent, the large dimension of steps resulted in the high integrated electromyogram val-ues when inclination was fixed; on the other hand, in the case of the fixed dimension of steps, the steep inclination caused the high integrated electromyogram values (Fig11). During descent, larger dispersion and smaller changes in the integrated electromyogram values than ascent were observed.

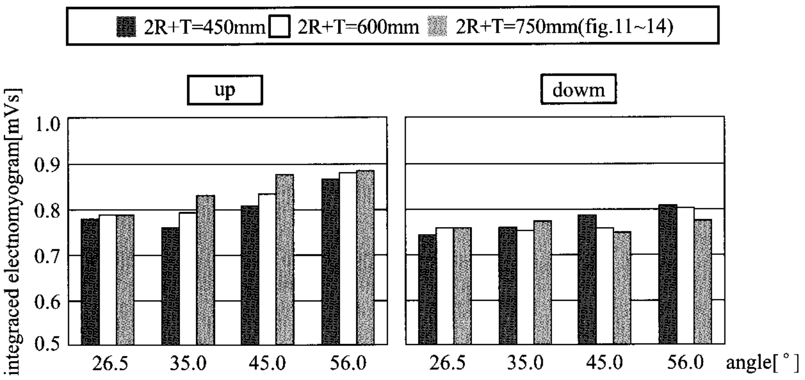

Fig. 11The integrated electromyogram values per walking cycle during ascent and descent depending on the inclination and dimension of steps

(3) Regarding the integrated electromyogram values after conversion to per unit height

After comparing the integrated electromyogram values depending on the inclination and dimension of steps con-verted to the values of each one meter ascent and descent during both ascent and descent, the integrated electromyogram values became high when the dimension of steps became small in the case of a fixed inclination. When the dimension of steps was fixed, steep inclination caused low integrated electromyogram values (Fig12). The reason for this result is considered that dimension of steps (mainly rise) was large or fewer numbers of footsteps were needed to reach the unit height on steep inclination than gradual inclination.

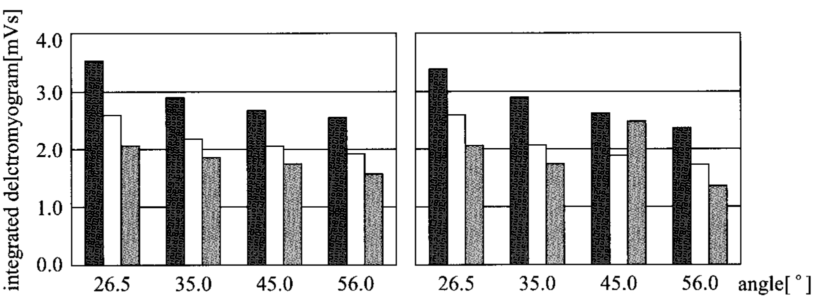

Fig. 12 The integrated electromyogram values after conversion to per unit height during stairway ascent and descent depending on the inclination and dimension of steps

3.4. Relationships among the inclination and dimension of steps, and leg joint angles

(1) Regarding the femoral angles

After evaluating the relationships among the inclination and dimension of steps, and leg joint angles during ascent and descent, the following results were obtained. During ascent, in the case of a fixed inclination, when the dimen-sion of steps increased, the femoral angles also increased. In the case of the fixed dimension of stairway, relatively constant femoral angles regardless of changes in inclination were obtained with few exceptions. In the case of a fixed stairway dimension, as inclination increases, rise dimension also increased; therefore, the femoral angles be-came large since a swing leg is needed to be raised to have a toe clear stair nosings. However, corresponding to increase of rise dimension, tread dimension decreased. As a result, the effects of increase and decrease on the femoral angles were counteracted each other (Fig13).

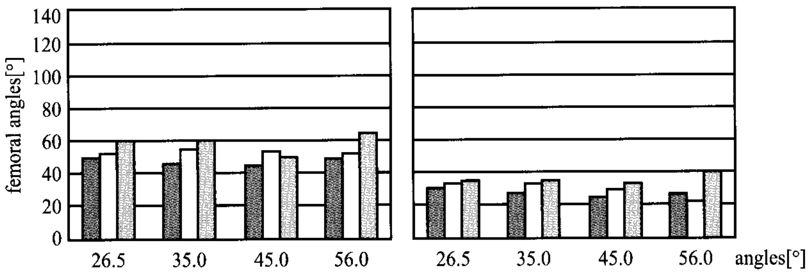

Fig. 13 The maximum femoral angles during ascent and descent depending on the inclination and dimension of steps

(2) Regarding the knee rotation angles

The relationships between the inclination and dimension of steps, and knee rotation angles during ascent and de-scent are presented. It was found that the knee rotation angles increased when the inclination or dimension of steps rose during both ascent and descent after comparing the changes in knee rotation angles depending on either inclina-tion or dimension of steps. In addition, knee rotation angles during ascent were maximized from the middle to late swing phases. On the other hand, they were maximized in the initial swing phase during descent (Fig14).

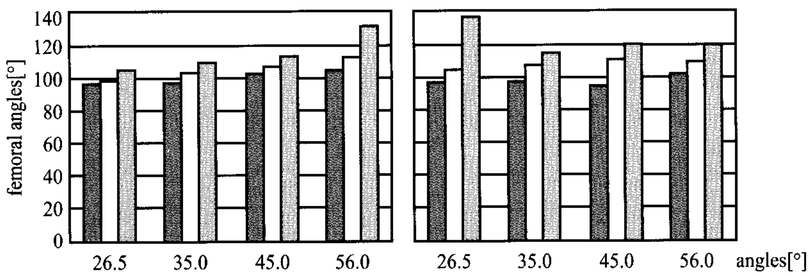

Fig. 14 The maximum knee rotation angles during ascent and descent depending on the inclination and d dimension of steps

3. 5 Comparison of effects on the integrated electromyogram values by quantification analysis type i targeting stairways

After comparing the level of effects on the integrated electromyogram values using quantification analysis type I, the following result was obtained. Inclination showed a stronger effect on the integrated electromyogram values than the dimension of steps by the analysis utilizing the mean of the integrated electromyogram values as an objective variable and 3 setting conditions as explanatory variables (Fig15). Obviously, muscle loads are considered to be the effect of inclination determines the amount of the energy of ascent and descent movement; on the other hand, leg joint angles may be the effect of dimension of steps determines stride length.

item	category	category score	total average evaluate:0.795 (-0.04 -0.02 0 0.02 0.04)	range
kind	up	0.027		0.054
	down	-0.027		
angle	26.5°	-0.027		0.068
	35.0°	-0.018		
	45.0°	-0.005		
	56.0°	-0.041		
2R+T	450mm	-0.007		0.015
	600mm	-0.001		
	750mm	0.008		

determination coefficient:0.788

Fig. 15 Comparison of effects by utilizing quantification analysis type I targeting stairways

3. 6. Comparison between ramps and stairways with the same dimension (about 600 mm)

The same testing was conducted on the multiple subjects on the same day. The errors due to differences in meas-urement time were considered to be at acceptable levels in terms of the accuracy of this study. Thus, the integrated electromyogram values per walking motion during ascent were compared by inclination in order (Figure 16 white bar graph: The values are presented on the left axis). On the ramp, the values are relatively constant regardless of the inclination; however, the values on the stairways are greater than the ramp showing an increase tendency with the rise of inclination angles. A predicted result was obtained regarding the conversion to per unit height showing that the steeper the inclination becomes, the fewer necessary muscle loads are (In Figure 16 line graph the values are pre-sented on the left axis in the parenthesis).

Regarding leg joint angles, constant values of femoral angles regardless of changes in the inclination of the ramp and stairways were obtained; on the other hand, although knee rotation angles maintained constant values on the ramp, the values significantly increased on the stairways and showed an increasing tendency in proportion to the amount of the inclination. It is suggested that this increase of knee rotation angles on the ramp and stairways is related to the amount of difference in the integrated electromyogram values (Figure 16 black and gray bar graphs: The values are presented on the right axis).

4. SUMMARY

The effects of changes in the ramp inclination and cross-section forms on muscle loads and leg joint angles were quantitatively grasped in the present study. By conducting the study serially comparing the

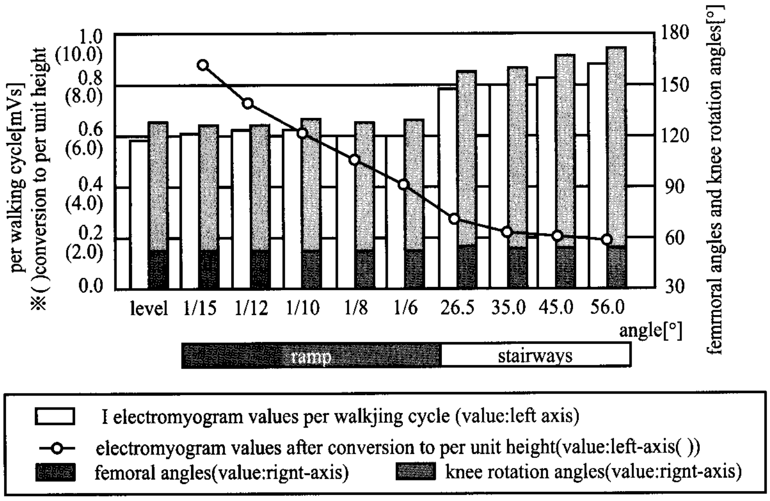

Fig. 16 The relationships between the integrated electromyogram values and leg joint angles (femoral angles and knee rotation angles) on the ramp and stairways in the case of 600 mm of the dimension of steps (2R + T).

effects of the gradual ramp to the steep stairway in the case of the fixed dimension of steps, we obtained interesting findings that increase of knee rotation angles is related to changes in muscle loads. However, this result was obtained under the limited conditions controlling the inclination and dimension of steps, and walking pace. Thus, future studies need to be conducted from different points of view since several other factors exists as variables in the real world.

REFERENCES

1. Hajime Nakajima, Evaluation of Mobility on slope, Summaries of technical papers of Annual Meeting Archi-tectural Institute of Japan, planning 55 pp745-746, 1998.
2. Ryouichi Takahashi, Experimental study on relation between actual form of body motion in ascending and de-scending stairs and an equation on rise and tread which is accepted as most proper, Summaries of technical papers of Annual Meeting Architectural Institute of Japan, E-1 pp745-746, 1998.
3. Kaori Kawamura, Study on dimensions of stairs and slopes accepted as proper from viewpoint of body motion in ascending and desc ending behavior, Summaries of technical papers of Annual Meeting Archi-tectural Institute of Japan, E-1, pp739-740, 1999.
4. Hidenori Ono, Examination on comparison of physiological load between the one step stair and THE slope in going up and down, Journal of structural and construction engineering. Transactions of Archi-tectural Institute of Japan, (601), pp31-36, 2006.
5. Tatuo Kto, Gait EMG analysis on an inclined walkway, Japanese Journal of Physical Fitness and Sports Medi-cine 56(5) p538, 2007.
6. Kengo Tarui, An experimental study on relationship of perceptional muscle load and phisical muscle load by electro-myogram during walking over difference of floor level, Summaries of technical papers of An-nual Meeting Architectural Institute of Japan, E-1, pp549-550, 2007.