Kose,S. Tsukuba, Japan; Endo,Y. & Uno,H. Narashino, Japan

SAFETY REQUIREMENTS FOR STAIRS IN DWELLINGS--ANALYSIS OF USER MOVEMENT

SUMMARY

Safety requirements of domestic stairs were studied by three different experimental methods. They were: Measurement of foot movement of the user by video camera; analysis of impact force by force platform; and energy requirements of stair climbing by heart rate. Oxygen intake on the treadmill was also measured to establish the applicability of heart rate as the estimate of energy consumption. Results suggest that minimum going should be 210 mm to assure firm support during descent; maximum rise be 180 mm to control body movement; but no limit was found from energy expenditure tests for dimensions of domestic stairs.

INTRODUCTION

Lots of researches have been conducted on stair dimensions. Most of them have concentrated their efforts on the problem of comfort, but it is quite clear that safety is more important if one only looks into the statistics of death and injury on stairs. In Japan, for example, 600 people die every year from stairway falls, and 60% of these fatal accidents occur in dwellings (Kose, 1982). Some studies have been directed toward the solution of this problem, and measures to mitigate undesirable aftermath of stairway accidents have been investigated (Kvarnstrom, 1977; Archea et al., 1979).

Previous research by Kose & Uno (1982) revealed that movement behaviour during descent is more critical than that during ascent, and that maximum allowable pitch is about 40°, minimum tread going around 200 mm. This conclusion was obtained from experiments in the laboratory and by observations, but no steep stairs like ones in dwellings were selected as the place of field study because few subjects were expected to be available.

The behaviour and response of the subjects may vary under different conditions, that in the present work more extensive study was carried out using experimental stairs. The present research also aimed at examining the applicability of the physiological conclusion drawn by Lehmann & Engelmann(1933) that the most comfort stair is 170 mm rise and 290 mm going with the pitch of 30.4°. This relation is still influential and always cited as appropriate dimensions for building stairs. However, a stair of such a gentle pitch seems too idealistic to be realized; most prevalent domestic stairs in Japan have the pitch of 45° or slightly steeper. Thus the question is whether physiological requirement is also a determining factor in designing stairs in domestic buildings, especially inside dwelling units, where the total difference in floor height is seldom more than three metres.

EXPERIMENTAL CONDITIONS FOR MOTION AND IMPACT FORCE STUDY

Five experimental stairs were set up in the laboratory with fixed rise of 150 mm, 165 mm, 180 mm, 195 mm, and 210 mm, and going dimensions adjustable from 150 mm to 330 mm enough to cover existing stairs in Japan (Maximum allowable stair within a single dwelling in Japan is 150 mm going and 230 mm rise; this 230 mm rise can be simulated by putting additional plywood on the treads). Each stair consisted of nine steps. The fact that stair users are very cautious at the start of the flight and become accustomed to the stair after two or three steps are completed, and that they also tend to change their behaviour just two or three steps before the end of the journey (Kvarnstrom, 1977), gives evidence of the need for at least 7 or 8 steps in a single flight of a stair as opposed to the shorter experimental apparatuses which previous researchers constructed.

Movement was recorded by a video rotary-shutter camera (Sony Inc.) which gives 30 clear still frames in a second, which are equivalent to pictures taken at the shutter speed of 1/500 second; they were transmitted to a video motion analyzer(Sony Inc.) and the movement was digitized by a video position analyzer(FOR.A Co.). Four university students participated in the experiments; they became quite accustomed to the experimental stairs before the measurement. Speed of traverse was not controlled; the subjects just used the stairs as if they were circulating normally. Kose & Uno(1982) found that the contact point of the ball joint of foot relative to the tread is most important to secure good balance of the body during descent. In this experiment, the actual length of foot jutting was measured from the video frame.

Impact force to the tread was measured by a KIAG piezoelectric force platform. It was placed on a stand that was independent from other steps of the experimental stair so that the vibration would not affect the platform. It served as the fourth step from the bottom. Signals of the platform were converted from analog to digital and processed by a micro-computer, and vertical and lateral force, torque, point of action and direction of force application were recorded on an X-Y plotter.

Six going sizes from 180 mm to 330 mm with the increment of 30 mm, and five riser heights from 150 mm to 210 mm with the increment of 15 mm were selected as experimental conditions for motion and impact force study. Nosing projection was 30 mm in all cases.

ANALYSIS OF ENERGY EXPENDITURE

There are several ways to estimate the amount of energy expended by human subjects, but detailed discussion requires oxygen consumption measurement. This is however quite tedious and time consuming, and it is nearly impossible to conduct it many times on stairs. As an alternative, the rate of heart beat was selected for an index of energy use, and its relationship with oxygen consumption was established by the measurement of treadmill walking in the laboratory.

It is well recognized that heart rate is easily affected by psychological load, and that heart rate itself differs from one subject to another. But as long as the application of the relationship is limited to himself, and to similar work load (in this case stair and sloped treadmill walking), heart rate can be a good estimate of energy requirements (Numajiri, 1974).

The treadmill at Juntendo University was used for energy consumption tests and three students participated as the subjects. It was run at the speed of 100 m/min in its direction, then the pitch was increased stepwise until the all-out condition was reached. Heart rate, oxygen consumption and breath rate were measured and relative metabolic rate (R.M.R.) was calculated as follows (Numajiri, 1974):

R.M.R.=Oxygen need during exercise/Basal oxygen consumption.

Oxygen need during exercise=Oxygen consumption during exercise
-Oxygen consumption during sedentary posture.

The latter relation applies here as the equilibrium is reached.

Next, the subjects walked up and down experimental stairs in the laboratory for the measurement of the work intensity of domestic stair climbing. Each subject was equipped with a portable heart rate memory apparatus, and the change of heart rate was printed out afterwards. The apparatus was capable of recording heart beat on an IC memory without a cable or a telemetering unit. Conditions for the experiment were: combination of going sizes 180 mm, 240 mm and 300 mm, and riser height 150 mm, 180 mm and 210 mm, and two additional conditions: (going)x(rise)= 150 x 210, and 330 x 150. Nosing projection was 30 mm in all cases just as before. Walking speed was set by a metronome at 18 m/min vertical height on the treads.

A stair of a highrise office building was used to measure the increase of heart rate during continuous climbing. The walking speed was the same as in the laboratory. The dimension of this stair was 170 mm riser and 260 mm going. All the subjects completed walking 104 m height difference in 6 min 40 sec.

RESULTS AND DISCUSSION

Fig.1 shows that the average position of the ball joint during descent is independent of the riser size but is related to the size of the tread. In the case of 180 mm going, the mean position of the ball joint was off from the tread. Detailed analysis of every trial of 180 mm going revealed that when the contact point is within the tread the foot is twisted crabwise so as to secure firm support. This twisting tendency was also witnessed by Ward & Randall(1967) in their experiments in the laboratory. Second order regression curve becomes:

$$y=-0.00169x^2+1.26x-174,$$ where x is going in mm and y is contact point of ball joint from nosing in mm.

The result suggests that the tread going should be at least 210 mm to secure firm support for the foot. This value is less than the recommendation by Pauls(1982). The discrepancy is partly due to the stature of people in question, and partly due to the difference in the interpretation of safe contact of foot with the tread.

Two peaks were obtained for each impact force at normal speed of traverse. During descent the first peak was larger. From Fig.2 it is evident that the change in going size gives little difference to the peak of the impact force during descent, whereas the change in riser height affects it. When the riser height was equal or less than 180 mm, the peak value remained independent of the riser height but with the increase of the height from 180 mm and on, it seemed to increase linearly. A separate calculation of regression lines suggests:

$y=-0.0278x+157$ if riser height$\leq$180 mm and
$y=0.923x-14.9$ if riser height$\geq$180 mm, where x is rise in mm and y is impact force relative to body weight in %.

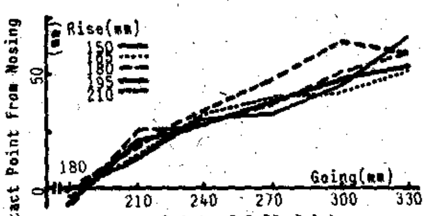

Fig.1 Contact Point of Ball Joint vs. Going Size

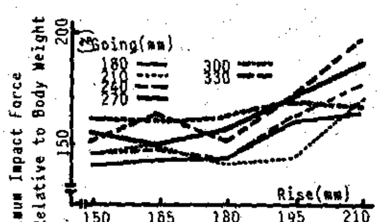

Fig.2 Maximum Impact Force vs. Rise

The change of tendency signifies that the control of impact force through the flexibility of the joint, especially of the knee joint, gradually loses its effectiveness as the height is increased. Thus, limiting the riser height to 180 mm is a measure for safety.

Almost linear relationship between R.M.R. and heart rate was obtained for each subject from the treadmill walking and applied to the interpretation of the results of other experiments. During continuous climbing of the highrise stair, heart rate rose up to about 150-180 beats per minute at the end of the travel, which gives estimated R.M.R. as high as 10 to 11; such high work intensity is seldom encountered among daily activities. Heart rate on experimental stairs rose from about 60-70 to 95-120 beats after one minute, which is in accordance with the result of Bruce et al.(1967), who got heart rate of 110-130 for the traverse speed of about 20 m/min vertical on the steps, faster than our 18 m/min. The heart rate gradually rose up to around 130 after five minutes of stair walking. Estimated R.M.R. lay within the range of 5-6 for three subjects for various cases. No dependence of R.M.R. on stair dimension was found when the speed of vertical traverse was controlled equal, a fair assumption for domestic stair use.

This leads to a conclusion that energy requirements on domestic stairs are of minor problem because there is little difference in work intensity between gentle and steep ones. Rather, the designing of such stairs should be directed to the assurance of safety against accidents. Out on the common stairs, where standard walking speed is likely to be imposed by other users, and also the stairs usually longer, the result of this experiment should not be applied.

Some of necessary conditions for safety on domestic stairs include: maximum riser height of about 180 mm; and minimum tread going of 210 mm. However, this is in conflict with the present normal dimensioning. As a remedy for this, proper handrails with reliable grip should be attached to prepare for critical incidents during traverse. Physical conditions for handrails are to be investigated.

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