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ORIGINAL ARTICLE

Relationship between life space and stair climbing among community-dwelling older adults

Ryunosuke Endo[1)], Atsumi Fukuda[2)], Masaya Kajino[3)], Koji Yoshikawa[1, 4)], and Eiki Tsushima[5)]

Abstract

Objective: Older adults often have difficulty in climbing stairs, leading to a limited life space and decreased quality of life. Stair climbing requires stability and smooth movement of the trunk and lower limbs. We investigated the relationship between living space and kinematic characteristics of stair ascending and descending.

Methods: This cross-sectional study enrolled 45 older adults who use an elderly daycare center ascended and descended 10-cm and 20-cm steps on a training staircase. Their truncal and knee movements on the frontal plane were quantified using the normalized jerk score (NJS) and normalized angular jerk cost (NAJC). Life-Space Assessment (LSA) for life space, Fall Efficacy Scale International (FES-I) for fear of falling, and Numeric Rating Scale (NRS) for pain were evaluated.

Results: LSA showed significant correlations with trunk NJS, knee NJS, and knee NAJC in the descending motion from 20-cm steps. After adjusting for age, sex, BMI, NRS, and FES-I, there were significant effects on trunk NJS, knee NJS, and knee NAJC in descending 20-cm steps.

Conclusion: Since the descending motion requires stability and braking against rapid motion, jerk is a suitable index to express motion smoothness. These findings indicate the importance of focusing on the kinematic characteristics of stair climbing behavior in assessing life space.

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Key words: Older adults; Life space; Stair ascending and descending; Jerk.

Introduction

For older adults, maintaining the quality of life (QOL) is important and also challenge for the aging society because QOL is possibly to be affected by the narrowing of the life space which represents one's range of daily activities[1)]. Various factors affect the life space for the group negatively; physical factors such as mobility[2, 3)], activities of daily life (ADL)[2, 3)] and physical activity[4)]; mental factors such as depression[5)] and fear of falling[6)]; environmental conditions of the residence and roads surrounding the home[7)]. In particular, mobility as ascending and descending stairs, which is the representative motion of the ability, is directly related to the life space because the ability is necessary to move from indoors to outdoors. Older adults have a reduced life space, possibly because they have difficulty ascending and descending stairs[8)].

Stability against undesirable lateral motion of the knee joint is required to perform stair ascending and descending motion smoothly and safely[9)]. In addition, the knee varus and valgus movements[10)] and shifting center of gravity of human body are larger in older adults than in

1) Doctor's degree program, Division of Comprehensive Rehabilitation Sciences, Hirosaki University Graduate School of Health Sciences.
2) Elderly health laboratory, Aomori, Japan
3) Department of Rehabilitation, National Hospital Organization Yanai Medical Center, Yamaguchi, Japan
4) Department of Rehabilitation, Ogata orthopedic clinic, Ehime, Japan
5) Division of Comprehensive Rehabilitation Sciences, Hirosaki University Graduate School of Health Sciences, Aomori, Japan

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✉：Ryunosuke Endo Division of Comprehensive Rehabilitation Sciences, Hirosaki University Graduate School of Health Sciences
E-mail: ryuendou1@gmail.com

the youth[11]. Furthermore, they often have difficulty in controlling the knee joint and the center of gravity, which may be a distress for them ascending and descending the stairs[12]. Therefore, it is necessary to evaluate the stability of the lower limbs and trunk during the stair ascending and descending movement of older adults living in small life space without losing balance or control from the kinematic perspective.

Jerk is an index used to evaluate stability and sway in motion analysis. It indicates the rate of change acceleration pace per unit of time and expresses the smoothness of motion. Higher jerk values indicate the loss of smoothness and the gain of speed in motion. Kinematically, Jerk indicates the dynamic lateral balance of the trunk as weight shift control[13], and it is also reported as an index of knee joint loading[14]. Although the significance of jerk varies depending on the body part and movement, this index can evaluate stair ascending and descending motion from a kinematic viewpoint. We hypothesized that lower the smoothness of the movement of the trunk and the knee joint during the stair-climbing motion, the smaller the life space of older adults have. In contrast, environmental factors and mental factors such as fear of falling also affect stair ascending and descending behavior by the different mechanism[15]. Therefore, it is necessary to investigate the influence of stair ascending and descending behavior on the life space for older adults by kinematic index, after accounting for confounding factors.

This study aimed to clarify whether the smoothness of trunk and knee movements in both stair ascending and descending movements are related to the life space and whether they affect the life space, even after adjusting for confounding factors related to stair ascending and descending.

Materials and methods

Participants

The participants were 45 older adults who used an elderly daycare center in Hirosaki, Aomori, Japan. The study was conducted from November 2019 to January 2020. The participants were those who could walk more than 10 meters indoors without assistance. Exclusion criteria were as follows: dementia diagnosed by a physician, neuromuscular disease with sensory or motor dysfunction, cerebrovascular disease, and orthopedic disease that severely limits the range of motion of the lower limbs including all the interruption to complete the stair ascending and descending motion. The purpose and procedure of the present study were explained to the participants beforehand, and written consent to participate in the study was obtained. All research procedures were approved by the Ethics Committee of the School of Health Sciences and Graduate School of Health Sciences in Hirosaki University (Approval Number 2019-040) and were conducted in accordance with the guidelines set forth in the Declaration of Helsinki.

Measurement

Height and weight were measured for all participants, to calculate their body mass index (BMI). Age, sex, and medical history were obtained from the medical record by the physician in charge, the information sheets from care managers in charge of the participants, or interviews with the participants. The Life Space Assessment (LSA) was used as the main outcome, and the Fall Efficacy Scale International (FES-I) and Numeric Rating Scale (NRS) were used as confounders; they were all evaluated based on the interviews by the first author. Ascending and descending stairs of 10-cm and 20-cm steps were recorded by the video camera.

LSA[2] is the scale that quantitatively

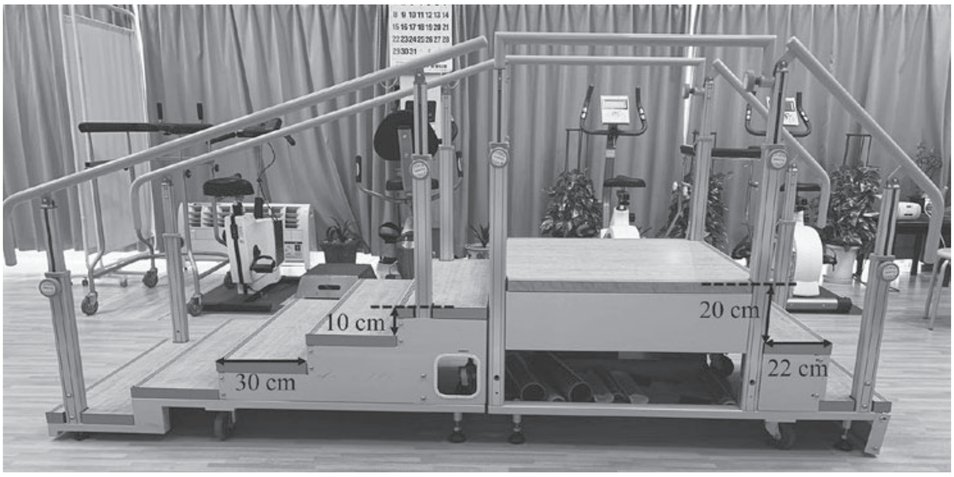

Fig. 1 Training stairs used for movement tasks.

measures the range of sphere of daily life and the independence of the activities within the sphere based on the level of assistance required respectively. The LSA consists of 0 to 120 points which scores the distance of locomotion within sphere of everyday life. Higher score indicates wider range and higher level of activities which the subject has. FES-I is the scale that assesses fear of falling based on self-efficacy of the subject against falling[16], which consists of 16 questions related to the activities of daily life. Subjects report their degree of confidence in their ability to complete the specific activities without falling with a four-point scale ranging from 1 (completely confident) to 4 (not confident at all); thus, higher number of the total score indicates lower self-confidence regarding falling or higher fear of falling. Pain during the motion was assessed using the NRS. Those who had pain in any part of the body were asked to rate the pain intensity on a 10-point scale ranging from 0, no pain to 10, the most severe pain one can imagine.

The digital camera (EX-FH100, CASIO, Japan, resolution: 640×480-pixel, sample frequency: 120 Hz) was used to measure the stair ascending and descending motion. Ten-cm steps (riser height: 10 cm, tread depth: 30 cm, six steps) and 20-cm steps (riser height: 20 cm, tread depth: 22 cm, three steps) of the training staircase (SP-100, SAKAI med, Japan, total length: 3 m) were used for the exercise task (Fig. 1). The digital camera was set in front of the participant to capture the movement in the frontal plane of the participant during the stair ascending and descending motion. The digital camera was positioned 7 m and 30 cm from the edge of the step at the height of 1 m and 30 cm during the ascending motion, and 3 m and 50 cm from the edge of the step at the height of 80 cm during the descending motion, and the camera was fixed perpendicular to the floor. Additionally, another digital camera was installed at the side of the participant to measure the timing of plantar contact of the foot from the sagittal plane. The position of the second camera was 2 m and 10 cm to the side of the stairs and at the height of 1 m and 10 cm (Fig. 2). Those two cameras on the frontal and sagittal planes were synchronized to capture the participant's motion simultaneously. Participants wore black undergarments, and stickers with a diameter of 2 cm were placed on the following landmarks: the manubrium of sternum on the frontal plane of the body; the anterior superior iliac spine (ASIS); the center of the patella; as well as the center of the fibular lateral malleolus and tibial medial malleolus of the foot. The participants were instructed to ascend and descend stairs as

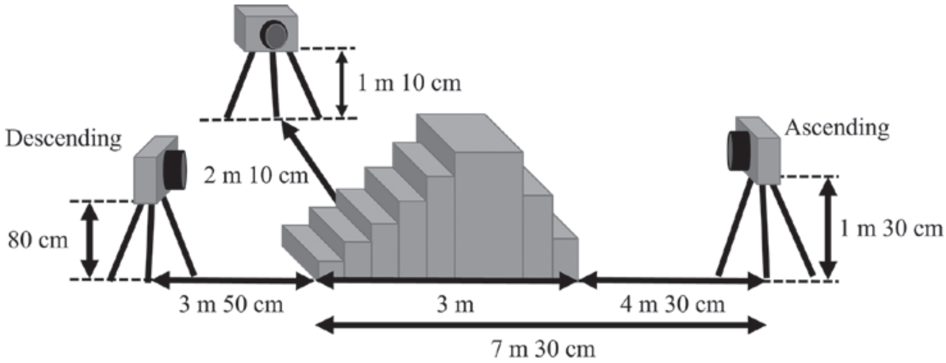

Fig. 2 Stairs and camera position. The figure shows the layout for ascending and descending stairs with 10-cm steps.

quickly as possible, one foot on each step. Participants were filmed while ascending and descending the 10-cm and 20-cm steps in two patterns: one by starting on the right foot, and another on the left foot. In the measurements, these trial patterns were performed and recorded once at a time. For safety precautions, participants were instructed to grasp the handrail during the task.

Data processing

We used Kinovea 0.9.3 (open source) to analyze the video data from the frontal plane of the stair ascending and descending climbing motion. During the single-leg bearing phase in the observed side, the segment of the video was extracted from the synchronized data and used for analysis. Both legs in the same phase were observed and analyzed. These analysis sections are when the lower limb of the observed side is supporting alone (Fig. 3) based on the definition of ascending motion and descending motion as follows. We defined the ascending motion as the interval from when the sole of the contralateral foot leaving the step to touching the one step above. Likewise, the descending motion is defined as the interval between from when the sole of the contralateral foot leaves the step to touching the one step below. From the video data, we analyzed the trajectory of each landmark in these sections.

Fig. 3 The analysis section for ascending and descending motions. The ascending (left figure) is the section from the time the contralateral lower limb leaves the ground to the time it touches the upper step. The descending step (right figure) is the section from the time the contralateral lower limb leaves the ground to the time it touches the lower step.

For the trajectory data, a low-pass filter (Butterworth, 2nd order, cut-off frequency: 5 Hz) was applied. Normalized jerk score (NJS) and normalized angular jerk cost (NAJC) were used to evaluate the smoothness of motion. NJS is an index of the jerk of the landmark, and NAJC is an index of the angularity of the joint angle, where lower values indicate smoother motion. We used the trajectory data of the manubrium of sternum as an index of the trunk in addition to the data from the center of the patella as the index of the knee joint. The calculated jerk was obtained from the trajectory data. The angle of lateral flexion of the trunk on the frontal plane was calculated when the angle between the midpoint of the line connecting the manubrium of the sternum and the bilateral ASIS, as well as the ASIS on the side of the observed lower limb. On the other hand, the angle of abduction of the knee joint was calculated as the angle between the ASIS of the observed lower limb and the patella, and the center of the fibular lateral malleolus and tibial medial malleolus in the ipsilateral side. The following two equations were used to calculate the trunk NJS, the knee NJS, the NAJC regarding the angle of lateral flexion of the trunk, and the NAJC regarding the angle of abduction of the knee joint for the ascending and descending movements on the 10-cm and 20-cm steps[17, 18]. The equations are as follows:

$$\text{Normalized Jerk Score} = \sqrt{\frac{t^5}{D^2}\int_0^t j^2\, dt}$$

$$\text{Normalized Angular Jerk Cost} = \frac{t^5}{2\left(\int_0^t \theta dt\right)^2}\int_0^t \left(\frac{d^3\theta}{dt^3}\right)^2 dt$$

t represents the time of the analyzed segment, *D* is the trajectory length of the landmark in the analyzed segment, *j* is the jerk calculated from the trajectory data, and θ is the angle. Numerical calculations were performed using the R 4.1.2 (CRAN).

Statistical analysis

For NJS and NAJC, the mean values of the trials were calculated for the right and left observed limbs, which was used for analysis. Dataset for 6 individuals who could not perform the task by 20-cm steps but could complete the task on 10-cm steps, were excluded because of the missing data. Spearman's rank correlation coefficient was used to analyze the relationship between LSA, trunk NJS, and knee NJS, as well as the trunk NAJC and knee NAJC. The regression coefficients of NJS or NAJC were obtained by multiple linear regression model with LSA as the dependent variable and NJS or NAJC, age, sex, BMI, NRS, and FES-I as the independent variables to eliminate the confounding effects of age, sex, BMI, pain, and fear of falling. The movement of the participants were classified into eight patterns (i.e., two types of steps [10-cm or 20-cm], two types of motions [ascending and descending], and two analyzed body parts [the trunk and knee joint]). Each of the NJS and NAJC has eight patterns of the movement, so that 16 models were created for the analysis. The NJS and NAJC were log-transformed to obtain normality, which was confirmed by the Shapiro–Wilk test. To facilitate interpretation, the dependent and independent variables were standardized. The significance level was set at p=0.05, and the R 4.1.2 (CRAN) was used for statistical analysis.

Results

1. Relationship between LSA and NJS, NAJC

The basic characteristics and outcomes of the participants are shown in Table 1. Overall, participants were 84.3 years old (SD = 4.8) and had LSA of 63.4 points (SD = 12.8). Table 2 shows the NJS and NAJC for stair climbing and descending movements, with values ranging from 16.7×10^9 to 73.6×10^{24}. Table 3 shows the Spearman's rank correlation coefficients of the kinematic data of the NJS, NAJC, and LSA. The rank correlation coefficients with the LSA showed significant correlations between trunk NJS and knee NJS and knee NAJC.

2. Regression coefficients for NJS and NAJC adjusted for age, sex, BMI, pain, and FES-I

As in the results of bivariate correlation, the

Table 1. Characteristics and outcomes of the study participants

	overall (n = 45)	20cm steps (n = 39)
Age (years)	84.3 (4.8)	84.8 (4.7)
Sex (male/female)	8/37	7/32
Height (cm)	146.3 (8.1)	146.7 (8.1)
Weight (kg)	50.5 (9.8)	51.0 (10.2)
BMI (kg/m^2)	23.5 (3.3)	23.6 (3.5)
Musculoskeletal disorders	18	14
Knee osteoarthritis (unilateral/bilateral)	1/8	1/8
Lumber musculoskeletal disorders	8	8
Cerebrovascular disorders	4	4
Pain on ascending and descending stairs		
Yes/No	8/37	7/32
Degree of pain for those with pain		
NRS	6.1 (1.7)	5.9 (1.7)
Pain location		
One side knee	5	4
Two side knees	2	2
Lumber	1	1
Daily use of stairs (Yes/No)	22/23	21/18
FES-I	29.2 (9.5)	29.0 (9.3)
LSA	63.4 (12.8)	64.5 (12.1)

Mean (SD)

Table 2. NJS and NAJC of stair ascending and descending movements of study participants

	10 cm steps (n = 45)		20 cm steps (n = 39)	
	Ascending	Descending	Ascending	Descending
Trunk NJS	10.3×10^{10} (37.5×10^{10})	17.2×10^{10} (81.4×10^{10})	16.7×10^{9} (52.7×10^{9})	55.1×10^{9} (20.2×10^{10})
Knee NJS	26.6×10^{12} (12.8×10^{13})	24.2×10^{10} (70.5×10^{10})	48.8×10^{10} (25.1×10^{11})	56.2×10^{10} (16.0×10^{11})
Trunk NAJC	24.8×10^{21} (14.2×10^{22})	19.6×10^{23} (12.8×10^{24})	15.2×10^{20} (88.7×10^{20})	73.6×10^{24} (42.1×10^{25})
Knee NAJC	25.7×10^{22} (16.4×10^{23})	19.5×10^{21} (93.4×10^{21})	19.8×10^{20} (10.3×10^{21})	10.1×10^{23} (60.8×10^{23})

Mean (SD)

Table 3. The correlation between LSA and NJS, NAJC

	10 cm steps (n = 45)		20 cm steps (n = 39)	
	Ascending	Descending	Ascending	Descending
Trunk NJS	−0.18 (−0.45, 0.12)	−0.20 (−0.46, 0.10)	−0.23 (−0.51, 0.09)	−0.40* (−0.63, −0.09)
Knee NJS	−0.17 (−0.44, 0.13)	−0.26 (−0.52, 0.03)	−0.12 (−0.42, 0.20)	−0.46* (−0.68, −0.17)
Trunk NAJC	−0.20 (−0.47, 0.10)	−0.14 (−0.42, 0.16)	−0.03 (−0.34, 0.29)	−0.26 (−0.53, 0.06)
Knee NAJC	−0.11 (−0.39, 0.19)	−0.15 (−0.42, 0.15)	−0.10 (−0.39, 0.23)	−0.40* (−0.63, −0.09)

*$p < 0.05$. Spearman's rank correlation coefficient (95% confidence interval)

results were significant for trunk NJS, knee NJS, and knee NAJC in the descending motion from 20-cm steps (See Table 4).

Discussion

In this study, we examined the relationship between LSA and the smoothness of trunk and knee movements during stair ascending and

Table 4. The regression coefficients of NJS and NAJC on LSA adjusted by multiple liner regression model

	10 cm steps (n = 45)		20 cm steps (n = 39)	
	Ascending	Descending	Ascending	Descending
Trunk NJS	−0.29 (−0.60, 0.02)	−0.21 (−0.51, 0.10)	−0.20 (−0.52, 0.11)	−0.35* (−0.63, −0.07)
Knee NJS	−0.24 (−0.54, 0.07)	−0.28 (−0.57, 0.02)	−0.26 (−0.60, 0.08)	−0.37* (−0.64, −0.10)
Trunk NAJC	−0.31 (−0.63, 0.01)	−0.18 (−0.48, 0.12)	−0.17 (−0.47, 0.13)	−0.28 (−0.57, 0.01)
Knee NAJC	−0.18 (−0.49, 0.13)	−0.18 (−0.48, 0.13)	0.01 (−0.31, 0.32)	−0.37* (−0.65, −0.10)

*$p < 0.05$. Regression coefficients (95% confidence interval)

descending motion. The results showed that the trunk NJS, knee NJS, and knee NAJC were negatively correlated with the LSA of descent from 20-cm steps. Since LSA increases as NJS or NAJC decreases, some participants who have difficulty in controlling the balance during abrupt movements such as ascending or descending stairs can be forced to live in smaller life spaces. Moreover, the relationship was also obtained after adjusting for confounding factors such as age, sex, BMI, pain, and FES-I.

While the jerk of the trunk is useful index for balance and stability during movements such as walking[13, 19] and some movements in the balance assessments[20, 21], the jerk of the knee joint is an index for interarticular weight loading in the lateral and medial directions. We can use jerk as an indicator of the load in the joint because the jerk is modified by the weight shifting in the knee joint while walking[14] as well as in the joint with deformity such as osteoarthritis[22]. Furthermore, it has been shown that the movement of the knee joint on the frontal plane affects an increase or decrease of the loading on the lower limb[14, 22]. Therefore, the jerk of the trunk and the jerk of the knee can be evaluated as a part of the physical function related to the stair climbing movement.

The stair descending motion is described as the motion toward the direction of gravity requiring the eccentric contraction mainly by the lower limb muscles. Maintaining the stability is difficult in going down rather than going up due to the acceleration of the body by the gravity force. Therefore, we consider that jerk is more sensitive in descending motion in comparison. Regarding the height of the step, we could not show a significant correlation between the NJS and NAJC on 10-cm steps and LSA. However, we can infer that the NJS and NAJC on 10-cm steps have a smaller correlation with the LSA than on 20-cm steps from the confidence interval we showed. This finding indicates that higher level of muscle response is required to surmount higher steps and steeper slopes[23]. Therefore, the higher the steps, the more difficult motion is required to maintain the smooth movement of the whole body. In addition, it may reflect the necessity of the physical function to expand the life space. In terms of the correlations and regression coefficients for NJS and NAJC, they are moderate effect sizes at best. Namely, the range of life activity for senior citizens is possibly influenced by mental and environmental factors as well as physical function.

The negative correlations between the trunk NJS, knee NJS, and knee NAJC in the descending motion on 20-cm steps for LSA shows the similar results in multiple linear regression model adjusted for age, sex, BMI, pain, and fear of falling. Older adults with a fear of falling often complain of difficulty in ascending and descending stairs[12]. Fear of falling also affects the life space[6], but the present results suggests that the association may be established only for the NJS and NAJC even after excluding the influence of fear of falling. This estimation indicates the physical functions are noteworthy and they can be related to stair ascending and descending in addition to the fear of falling when assessing the life space.

The participants of this study were older adults in a rural area who use a daycare facility. In contrast to healthy older adults in urban area, they may currently have or are expected to have a decline in physical function due to the age-related disability or disease. Physical inability among community-dwelling older adults causes social disabilities leading to social withdrawal or being bedridden to become a significant impact on social security[24]. The cutoff value of LSA for predicting the decline of Instrumental ADLs within a year is 56 points[25], and the cutoff LSA value for predicting the occurrence of ADL disability within two years is 52.3 points[26], but the mean LSA scores of the participants in this study were higher than either cutoff value. Older adults in this study were able to walk and had opportunities to go out with assistance and aids. In other words, they are considered to be in the category of people who have a certain amount of life space, albeit with some decline in physical functions at most. It is known that stair ascending and descending motion is specific from gait motion in terms of time-distance variables, actions of lower limb muscles, and joint angles[27]. Therefore, it is necessary to evaluate stair ascending and descending motion separately from gait motion because even older adults who have no difficulty in daily walking may have some problems with stair climbing in proportion to the working load. Consequently, it is important to link the life space and physical ability related to the stair ascending and descending movement, as was done in this study. However, the relevance to homebound older adults who do not use a daycare facility is unknown, and a large-scale verification with a wider range of subjects is needed to examine the heterogeneity of effects due to the differences in the sample.

There were several limitations in this study. First, among the participants who performed the 10-cm step task, some had difficulty in performing the 20-cm step task. Therefore, the analysis was performed on the data after excluding missing values. However, it is possible that the result of the task on the 20-cm step by the individuals with good physical function may have altered the results. Second, most of the participants were holding the handrails while stepping stairs for safety reasons along with the physical frailty. Hence, we needed to include all the participants regardless the usage of the handrails to avoid the significant reduction of the sample size. Lastly, the analysis was limited in the frontal plane of the stair ascending and descending motion during the support of single leg standing so that the sagittal plane was not observed in the present study. Therefore, other components such as the clearance of the free leg side and movement on the sagittal plane is unclear. Consequently, future study will be encouraged to apply more detailed measurement including the multiplane and/or bilateral analysis of the motion to provide further validity. Moreover, development of exercise protocol for older adults to expand their living space or predictive screening tools for the assessment based on the studies will be expected.

Conclusion

In the descending motion for 20-cm steps, trunk NJS, knee NJS, and knee NAJC were correlated with LSA. In the descent of a 20-cm step, there was a moderate correlation between LSA and NJS of the trunk, NJS of the knee joint, and NAJC of the knee joint. Jerk is a suitable index for representing the smoothness of the movement because the step-down movement requires stability and braking against rapid movements. Since living space is affected by mental and environmental factors in addition to physical functions, NJS and NAJC should be considered as factors to be taken into account when evaluating stair ascending and descending behavior along with other factors.

Conflict of interest

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors have no conflicts of interest to declare.

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