# A novel infrared laser device that measures multilateral parameters of stepping performance for assessment of fall risk in elderly individuals

***Running head: Step-Tracking Device Applying LRF for Fall Risk Assessment***


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## Abstract

### *[Background and Aims]*

Avoiding falls requires fast and appropriate step responses in real-life situations. We developed a step-tracking device that uses an infrared laser sensor for convenient assessment of stepping performance, including concurrent assessment of temporal and spatial parameters. In the present study, we created a new index for assessment of fall risk that uses step speed and accuracy measurements. The purpose of this study was to determine whether the new index could discriminate between elderly individuals with different risks of falling.

### *[Methods]*

152 community-dwelling elderly individuals (73.9 ± 4.6 years) participated and performed stepping tasks as quickly as possible on a plus-shaped mat in response to optical cues. The step-tracking device with the infrared sensor detected the motion and position of both legs in the step field. The device recorded temporal and spatial parameters, foot-off and foot-contact time, step length, and the percentage of correctly executed steps. We used the coefficients of a logistic regression model to develop "Stepping-response score" based on the weighted sum of these temporal and spatial parameters.

### *[Results]*

The faller group had significantly worse stepping-response score than the non-faller group ($p < 0.001$). A stepwise logistic regression analysis demonstrated that stepping-response score was independently associated with falling (odds ratio = 0.15; $p < 0.001$). The ROC curve had a moderate AUC (0.73) for stepping-response score (sensitivity 73.0%; specificity 69.7%).

### *[Conclusions]*

This study indicates that the stepping-response score calculated from measurements obtained using the new step-tracking device can identify elderly individuals who are at a risk of falling.

### *[Key words]*

Falls, Elderly, Stepping performance, Step-tracking device, Laser range finder

## 1. Introduction

One-third of community-dwelling elderly individuals aged over 75 years will experience at least 1 fall each year (1). Falling occurs in various situations of daily life and generally results from an interaction of multiple and diverse risk factors (2, 3). Falling is a common problem in the aging population; hence, more effective and convenient tools, than those currently available, are required for the assessment of fall risk, to enable better identification of people who are more likely to fall and who need preventive interventions.

Avoiding falls requires fast and appropriate step responses in real-life situations. Falls can arise from external perturbations (e.g. slips, trips, and collisions), but are also frequently a consequence of self-induced perturbation during volitional movement (e.g. turing, bending, and reaching). Voluntary stepping reaction time can identify elderly individuals who are at a risk of falling (4-8). The step responses for avoiding a fall are composed of several components, including motor and cognitive functions and visuospatial skills. Previous studies indicate that decreased reaction time (9, 10), reduced step length (11), and step accuracy (4, 12) affect balance control or are important indicators of fall risk. However, previous step-response tests made use of relatively fixed and specialized laboratory equipment (i.e. force platform) or assessed only step speed as the indicator of fall risk in elderly individuals.

In order to add some knowledge with regard to new objectively measured parameters, we developed a method to easily quantify stepping performance in terms of step speed, length, and accuracy. Our new device, which uses an infrared laser sensor (laser range finder [LRF]), can assess stepping performance conveniently. The device consists of only a LRF and a computer, and it can detect the motion of both legs. It measures temporal and spatial parameters of steps by measuring the distance and angle of the legs using the infrared laser sensor. In the present study, we took advantage of our device's ability to concurrently measure temporal and spatial parameters automatically to create a new index for assessment of fall risk that uses step speed and accuracy measurements. Measuring multilateral parameters of stepping performance seems more important for assessment of fall risk than measuring a single function.

The aim of this study was to determine whether the new index developed using the LRF device can discriminate between elderly individuals with different fall risks. We hypothesized that an index integrating temporal and spatial measurements, rather than traditional clinical measures, may help more successfully discriminate between elderly individuals with different fall risks.

## 2. Materials and Methods

### *2.1. Participants*

We recruited participants through advertisements in the local press requesting for healthy community-dwelling volunteers. In total, 152 Japanese participants living in Kyoto city who were 65 years and older (mean age, 73.9 ± 4.6 years) participated in this study. Participants were excluded if they had any of the following symptoms: (a) serious visual impairment (including cataracts, glaucoma, or color blindness), (b) inability to ambulate independently (those requiring the assistance of a walker were excluded), (c) a score of less than 5 on the rapid dementia screening test (RDST) (13), (d) symptomatic cardiovascular disease, (e) neurological and orthopedic disorders, (f) peripheral neuropathy of the lower extremities, or (g) severe arthritis. Written informed consent was obtained from each participant in accordance with the guidelines approved by the Kyoto University Graduate School of Medicine (approval number E-880).

Each participant was categorized as either faller group (F) or non-faller group (NF), based on self-reports of the occurrence of at least 1 fall within the past 1 year. Using a standardized questionnaire, a fall was retrospectively defined as an event that results in a person unintentionally coming to rest on the ground or any other lower level with or without injury or loss of consciousness (14).

### *2.2. Experimental Protocol*

Five 30 cm × 30 cm squares were arranged in a plus shape and participants started by standing upright in the center square. In the stepping performance task (see Figure 1), participants were instructed to step as quickly as possible into 1 of the 4 squares arranged around the starting position after receiving a visual cue indicating in which of the 4 directions they should step. Participants were instructed to step fully into the indicated square, with one foot followed by the other, and then to return to the center square. The direction participants were to step (forward, backward, right, or left), was indicated by an arrow on a computer monitor. The computer monitor was placed 1 m in front of the participants. Participants were instructed to gaze at the computer monitor while awaiting the cue, but were allowed to look at the mat prior to stepping. The stepping performance task consisted of 2 trials in each of the 4 stepping directions, for 8 consecutive trials. The entire task required a few minutes to complete. Visual cues, indicating the stepping direction, were presented in random order.

All participants also underwent 3 clinical measurements of motor function in the presence of an experienced physiotherapist; a 10-m walking test (WT) (15), timed up and go test (TUG) (16), and a 5-chair stand test (5CS) (17). To evaluate cognitive function, we administered the RDST and evaluated participant performance on a verbal fluency task. Both tests are very sensitive and economical psychometric screening tools for identifying patients with cognitive impairment (13, 18, 19). For the verbal fluency task, participants were instructed to name as many animals as possible in 1 minute. The score for this task was the number of animals the participants were able to name.

### *2.3. Data Collection and Analysis*

The temporal and spatial raw data obtained during the stepping performance task were collected with a step-tracking device (Murata Machinery, Ltd., Kyoto, Japan) of our own design that consisted of a LRF and a computer. To calibrate the device, the center position and angle of the stepping field were calculated geometrically by the LRF so that the stepping field can be coordinated. The LRF measured the distance and angle of the legs using the infrared laser sensor, and detected the motion of both legs. We used the leg detection algorithm proposed in a previous study (20). Although the conventional leg detection algorithm measured only the position of the center of the legs, our step-tracking device is capable of measuring both the position of the center of the legs and that of each leg. The time of movement initiation and step completion were obtained from the leg position and step velocity data. The foot-off time was defined as the time that the velocity of the leg movement started to increase and the foot-contact time was defined as the time that the velocity of the leg movement was less than the threshold. The computer extracted the temporal and spatial parameters using a program written in Microsoft Visual C+ (Microsoft Japan Co., Ltd., Tokyo, Japan). The details of the data analysis algorithms used in this system are described in our previous study (Matsumura et al., unpublished data).

The following temporal parameters were measured: (a) foot-off time of the leading leg (reaction time), defined as the time from the cue to the movement initiation of the leading leg and (b) foot-contact time of the trailing leg (stepping time), defined as the time from the cue to the completed second step. Step length was calculated as the difference of the center of both legs between the positional information of the starting position and that of the position after the second step. To assess the accuracy of reaction choices, we classified the stepping performance of each trial as correct, hesitant, or wrong. Correct stepping was defined as stepping with both legs in the correct direction. Hesitant stepping was defined as initially stepping with the leading leg in an incorrect direction, followed by stepping with both legs in the correct direction. Wrong stepping was defined as stepping with both legs in an incorrect direction. The computer program, based on spatial data, automatically classified the stepping performance of each trial. Correct stepping was scored as 1, hesitant stepping as 0.5, and wrong stepping as 0. The percentage of correctly executed steps was calculated from the average score of 8 trials.

Our previous study indicated that this stepping performance device had high test-retest reliability (inter-trial correlation coefficient (ICC) foot-off time = 0.810; foot-contact time = 0.831; $p < 0.001$), and had the capacity to measure foot-off and foot-contact time that were highly correlated with those measured using a force platform (foot-off time: $r = 0.997$; foot-contact time: $r = 0.879$; $p < 0.001$) (Matsumura et al., unpublished data).

### *2.4. Statistical Analysis*

Before analyzing stepping parameters (reaction time, stepping time, and step length), we removed the 11 steps that were classified as wrong stepping. In order to create a "Stepping-response score", a series of nested regression models was preliminarily used to determine which combination of parameters in a model provided a significantly better fitting regression than those in other candidate models. A model that included 3 parameters (age, reaction time, and the percentage of correctly executed steps) provided the best fit of other models, and we calculated a multiple logistic regression model that included these parameters. Based on the coefficients from this model, we developed the "Stepping-response score" that used a weighted sum of the following step assessment parameters: age, reaction time, and the percentage of correctly executed steps. To calculate the stepping-response score, the antilog of the coefficient associated with each predictor was multiplied by the predictor. The stepping-response score was calculated as follows: stepping-response score = - {- 3.051 + (0.071 × age) + (2.521 × reaction time) + (- 0.054 × percentage of correctly executed steps)}. As the domain of stepping-response score, we grouped reaction time of all directions together because the directional specificity of the stepping performance task was not shown in the preliminary analysis.

We used Student's *t* test for independent measures to evaluate differences between the stepping performance parameters of F and NF. A multivariate logistic regression analysis using a stepwise method was performed to determine whether these measurements were independently associated with falling. For this analysis, F and NF were the dependent variables and those measurements that were significantly different between groups were the independent variables. For the independent variables that remained in the final step of the regression model, odds ratios (ORs) with 95% confidence intervals (CI) were presented. We then calculated the area under the receiver operating characteristic (ROC) for the independent variables that remained in the final step of the regression model. The sensitivity and specificity of these variables were also calculated based on the ROC curve.

Data were analyzed using the Statistical Package for the Social Sciences (SPSS, Windows version 20.0, SPSS Inc., Chicago, IL, USA). *P*-values less than 0.05 were considered statistically significant.

## 3. Results

### *3.1. Participant Characteristics*

A total of 41 F and 111 NF elderly individuals participated in the study. The demographic and performance characteristics of participants in both groups are shown in Table 1. Participants in the F group were significantly older those in the NF group. F participants took significantly longer to complete the WT, TUG, and 5CS tests than NF participants. There were no significant differences in other variables between groups.

### *3.2. Group Comparisons*

The stepping performance parameters of both groups are shown in Table 2. F participants had significantly lower (worse) stepping-response score than NF participants ($p < 0.001$). F participants had significantly longer reaction time and stepping time than NF participants, whereas there were no significant differences in step length and percentage of correctly executed steps between groups.

### *3.3. Logistic Regression and ROC Analysis*

In the analysis, the measurements that were significantly different between groups (the stepping-response score, age, WT, TUG, 5CS, reaction time, and stepping time) were employed as independent variables. Stepwise logistic regression analysis indicated that the stepping-response score (OR = 0.15; 95% CI = 0.12– 0.51; $p < 0.001$) and 5CS (OR = 1.23; 95% CI = 1.04 – 1.45; $p = 0.015$) were the independent variables that remained in the final step of the regression model and were therefore considered to be independently associated with falling (Table 3). The ROC curve had a moderate area under the curve (AUC) for stepping-response score (0.73) and a low AUC for 5CS (0.65). The sensitivity of the stepping-response score was 73.0%, and the specificity was 69.7%.

## 4. Discussion

This is the first study using a stepping performance device that integrates temporal and spatial measurements to identify elderly individuals at a risk for falling. Quick step execution (5, 8) and step accuracy (4, 12) are important skills that can serve to alter the support base, preserve stability, and prevent a fall. Our step-tracking device that uses an infrared laser sensor can conveniently assess these components of stepping performance. Previously, a similar portable device that included a dance mat step-timing device was used to easily assess stepping performance parameters (21). Since our new device can also assess stepping performance step speed, length and accuracy, it may be useful for determining fall risk.

Similar to previous studies (5-7), the present study showed participants with a history of falls had significantly longer stepping reaction times than those with no history of falls. The stepping-response score we developed that integrates temporal and spatial measurements can discriminate between participants with and without a history of falls with good sensitivity using a logistic regression and discriminant analysis. Avoiding falls in real-life situations requires fast and appropriate step responses, and the speed and accuracy of responses can be indicated by the step speed and accuracy measurements used in the present study. In the results of the present study, there was no significant difference in step accuracy measurement, probably because of the comparatively easy stepping performance tasks. However, formulating a stepping-response score that integrates temporal and spatial measurements was the most reasonable index (preliminary regression analysis) among the candidate indexes (e.g. the model: age and reaction time) and could successfully identify individuals at risk of falling. This may be because step accuracy measurement was related to the risk of falling as an internal factor in our stepping performance task. We will need to investigate this more thoroughly in a future study. Although previous rapid step reaction tests used only step speed as a fall risk indicator for elderly individuals (8, 22), the prevention of falls may require the assessment of multiple aspects of step responses. The stepping-response score in this study is the first index that assesses the risk of falls from the perspective of step speed and accuracy. Moreover, stepping-response score was mildly correlated with motor and cognitive functions (results not shown). Therefore, this stepping-response score is a novel index that assesses fall risk from a new perspective.

The new step-tracking device developed is fairly inexpensive and portable in comparison to other step performance assessment tools. These characteristics enable its use at clinical sites. Furthermore, our device does not require specialized personnel, and the difficulty of the stepping task can be adjusted according to the subjects undergoing assessment. For example, we could ask participants to step in a direction contrary to that indicated by the arrow on the computer monitor. Therefore, the device has high utility and can be used in clinical settings or in homes of elderly individuals as both an assessment tool and a training device. Recent intervention studies have indicated that abilities relating to voluntary stepping can be improved by training (23, 24). Elderly individuals are also able to improve their balance under dual task (DT) conditions after specific DT balance training (25, 26). In a previous study, we reported that a rhythmic stepping exercise under cognitive conditions like the task of present study improved DT function (26). This exercise has potential as a means of public health promotion, as it can be performed within a small indoor space. Our device can also serve as a training aid and can be used to facilitate effective exercise at community and clinical sites. A prospective cohort study is needed to further evaluate the relationship between falling incidents and stepping-response score. We hope that our device is not only useful for fall assessment but also opens avenues for developments in cognitive-locomotion science.

There are several potential limitations in present study. First, we retrospectively investigated the risk of falls, based on participants' experience of falls within the year preceding the study. Therefore, the accuracy of our device in predicting future falls among elderly individuals was not measured. Examination of the validity of the predictions made using measurements from this device requires a prospective investigation of occurrence of falls. The second limitation is that all participants in the present study were robust elderly individuals with high functional capacity. A previous study reported that DT performance was a reliable predictor of falls in a robust elderly population (27). Therefore, our results may apply only to robust elderly individuals. We need to investigate the stepping performance in frail elderly individuals to prevent falls among all community-dwelling elderly individuals.

## 5. Conclusions

The present study indicates that our new stepping performance device that uses LRF can be an effective clinical tool to identify high risk elderly individuals and the measurements obtained using this device reflect multilateral parameters, such as motor and cognitive functions. The new index we developed that integrates temporal and spatial measurements can successfully discriminate between participants who are at a high and low risk of falling.


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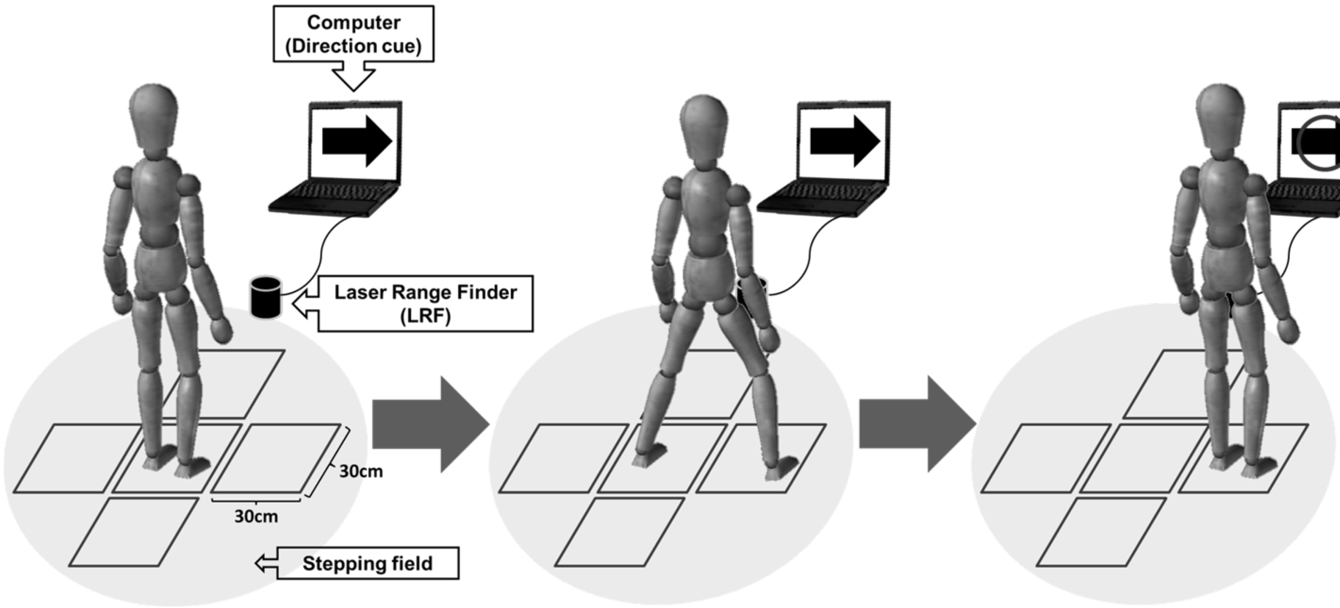


Figure 1. Schematic representation of the step-tracking device and the stepping performance task. The circle represents the stepping field in which the infrared laser sensor can detect the motion of both legs. Participants initially stood upright in the center square of five 30 cm × 30 cm squares arranged in a plus shape. Participants were instructed to quickly step with one leg, followed by the other leg into 1 of the 4 squares arranged around the starting position when provided with a visual cue indicating which direction to step.

Table 1. Characteristics of community-dwelling participants aged 65 and older with and without a history of falls.

| | F (n = 41) | NF (n = 111) | *p*-value |
|---|---|---|---|
| Age (y) | 75.4 ± 4.6 | 73.5 ± 4.6 | 0.025* |
| Gender (% men) | 26.8 | 44.1 | 0.062 |
| Height (cm) | 152.0 ± 8.6 | 155.1 ± 8.5 | 0.053 |
| Weight (kg) | 55.0 ± 9.4 | 54.8 ± 11.5 | 0.927 |
| RDST | 9.08 ± 2.25 | 9.63 ± 2.53 | 0.237 |
| Verbal fluency task | 12.8 ± 3.0 | 13.4 ± 3.9 | 0.357 |
| WT (s) | 8.06 ± 1.48 | 7.22 ± 1.04 | < 0.001** |
| TUG (s) | 7.05 ± 1.09 | 6.45 ± 1.34 | 0.012* |
| 5CS (s) | 9.66 ± 3.07 | 8.26 ± 1.89 | 0.010* |

Note: F = faller group; NF = non-faller group; RDST = rapid dementia screening test; WT = 10-m walking test; TUG = timed up and go test; 5CS = 5-chair stand test

*$p < 0.05$. **$p < 0.01$.

Table 2. Comparison of the stepping performance parameters measured in elderly community-dwelling participants.

| | F (n = 41) | NF (n = 111) | *p*-value |
|---|---|---|---|
| Reaction time (s) | 0.85 ± 0.17 | 0.78 ± 0.11 | 0.013* |
| Stepping time (s) | 1.65 ± 0.30 | 1.55 ± 0.18 | 0.004** |
| Step length (cm) | 27.0 ± 4.2 | 27.4 ± 4.2 | 0.831 |
| Correctly executed steps (%) | 96.8 ± 7.6 | 98.3 ± 3.6 | 0.256 |
| Stepping-response score | 0.76 ± 0.80 | 1.19 ± 0.54 | < 0.001** |

Note: F = faller group; NF = non-faller group

*$p < 0.05$. **$p < 0.01$.

Table 3. Factors associated with falling in stepwise logistic regression analysis.

| Dependent Variable | Odds Ratio (95% CI) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Stepping-response score | 5CS | age | WT | TUG | Reaction time | Stepping time |
| Faller or non-faller | 0.14 (0.12 – 0.51)** | 1.23 (1.04 – 1.45)* | - | - | - | - | - |

Note: 5CS = 5-chair stand test; WT = 10-m walking test; TUG = timed up and go test

*$p$ < 0.05. **$p$ < 0.01.