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

3
4 **Running head: Step-Tracking Device Applying LRF for Fall Risk Assessment**

5
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2

1 **Abstract**

2 **[Background and Aims]**

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

9 **[Methods]**

10 152 community-dwelling elderly individuals (73.9 ± 4.6 years) participated and performed
11 stepping tasks as quickly as possible on a plus-shaped mat in response to optical cues. The
12 step-tracking device with the infrared sensor detected the motion and position of both legs in the
13 step field. The device recorded temporal and spatial parameters, foot-off and foot-contact time,
14 step length, and the percentage of correctly executed steps. We used the coefficients of a logistic
15 regression model to develop “Stepping-response score” based on the weighted sum of these
16 temporal and spatial parameters.

17 **[Results]**

18 The faller group had significantly worse stepping-response score than the non-faller group ($p <$
19 0.001). A stepwise logistic regression analysis demonstrated that stepping-response score was
20 independently associated with falling (odds ratio = 0.15; $p < 0.001$). The ROC curve had a
21 moderate AUC (0.73) for stepping-response score (sensitivity 73.0%; specificity 69.7%).

22 **[Conclusions]**

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

25

26 **[Key words]**

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

28

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. turning, 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

1 can discriminate between elderly individuals with different fall risks. We hypothesized that an
2 index integrating temporal and spatial measurements, rather than traditional clinical measures, may
3 help more successfully discriminate between elderly individuals with different fall risks.

4 5 **2. Materials and Methods**

6 ***2.1. Participants***

7 We recruited participants through advertisements in the local press requesting for healthy
8 community-dwelling volunteers. In total, 152 Japanese participants living in Kyoto city who were
9 65 years and older (mean age, 73.9 ± 4.6 years) participated in this study. Participants were
10 excluded if they had any of the following symptoms: (a) serious visual impairment (including
11 cataracts, glaucoma, or color blindness), (b) inability to ambulate independently (those requiring
12 the assistance of a walker were excluded), (c) a score of less than 5 on the rapid dementia
13 screening test (RDST) (13), (d) symptomatic cardiovascular disease, (e) neurological and
14 orthopedic disorders, (f) peripheral neuropathy of the lower extremities, or (g) severe arthritis.
15 Written informed consent was obtained from each participant in accordance with the guidelines
16 approved by the Kyoto University Graduate School of Medicine (approval number E-880).

17 Each participant was categorized as either faller group (F) or non-faller group (NF), based on
18 self-reports of the occurrence of at least 1 fall within the past 1 year. Using a standardized
19 questionnaire, a fall was retrospectively defined as an event that results in a person unintentionally
20 coming to rest on the ground or any other lower level with or without injury or loss of consciousness
21 (14).

22 23 ***2.2. Experimental Protocol***

24 Five 30 cm × 30 cm squares were arranged in a plus shape and participants started by standing
25 upright in the center square. In the stepping performance task (see Figure 1), participants were
26 instructed to step as quickly as possible into 1 of the 4 squares arranged around the starting
27 position after receiving a visual cue indicating in which of the 4 directions they should step.
28 Participants were instructed to step fully into the indicated square, with one foot followed by the

1 other, and then to return to the center square. The direction participants were to step (forward,
2 backward, right, or left), was indicated by an arrow on a computer monitor. The computer monitor
3 was placed 1 m in front of the participants. Participants were instructed to gaze at the computer
4 monitor while awaiting the cue, but were allowed to look at the mat prior to stepping. The stepping
5 performance task consisted of 2 trials in each of the 4 stepping directions, for 8 consecutive trials.
6 The entire task required a few minutes to complete. Visual cues, indicating the stepping direction,
7 were presented in random order.

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

17 **2.3. Data Collection and Analysis**

18 The temporal and spatial raw data obtained during the stepping performance task were collected
19 with a step-tracking device (Murata Machinery, Ltd., Kyoto, Japan) of our own design that consisted
20 of a LRF and a computer. To calibrate the device, the center position and angle of the stepping
21 field were calculated geometrically by the LRF so that the stepping field can be coordinated. The
22 LRF measured the distance and angle of the legs using the infrared laser sensor, and detected the
23 motion of both legs. We used the leg detection algorithm proposed in a previous study (20).
24 Although the conventional leg detection algorithm measured only the position of the center of the
25 legs, our step-tracking device is capable of measuring both the position of the center of the legs
26 and that of each leg. The time of movement initiation and step completion were obtained from the
27 leg position and step velocity data. The foot-off time was defined as the time that the velocity of
28 the leg movement started to increase and the foot-contact time was defined as the time that the

1 velocity of the leg movement was less than the threshold. The computer extracted the temporal
2 and spatial parameters using a program written in Microsoft Visual C+ (Microsoft Japan Co., Ltd.,
3 Tokyo, Japan). The details of the data analysis algorithms used in this system are described in
4 our previous study (Matsumura et al., unpublished data).

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

18 Our previous study indicated that this stepping performance device had high test-retest reliability
19 (inter-trial correlation coefficient (ICC) foot-off time = 0.810; foot-contact time = 0.831; $p < 0.001$),
20 and had the capacity to measure foot-off and foot-contact time that were highly correlated with
21 those measured using a force platform (foot-off time: $r = 0.997$; foot-contact time: $r = 0.879$; $p <$
22 0.001) (Matsumura et al., unpublished data).

24 **2.4. Statistical Analysis**

25 Before analyzing stepping parameters (reaction time, stepping time, and step length), we
26 removed the 11 steps that were classified as wrong stepping. In order to create a
27 “Stepping-response score”, a series of nested regression models was preliminarily used to
28 determine which combination of parameters in a model provided a significantly better fitting

1 regression than those in other candidate models. A model that included 3 parameters (age,
2 reaction time, and the percentage of correctly executed steps) provided the best fit of other models,
3 and we calculated a multiple logistic regression model that included these parameters. Based on
4 the coefficients from this model, we developed the “Stepping-response score” that used a weighted
5 sum of the following step assessment parameters: age, reaction time, and the percentage of
6 correctly executed steps. To calculate the stepping-response score, the antilog of the coefficient
7 associated with each predictor was multiplied by the predictor. The stepping-response score was
8 calculated as follows: stepping-response score = $e^{-\{-3.051 + (0.071 \times \text{age}) + (2.521 \times \text{reaction}$
9 $\text{time}) + (-0.054 \times \text{percentage of correctly executed steps})\}}$. As the domain of stepping-response
10 score, we grouped reaction time of all directions together because the directional specificity of the
11 stepping performance task was not shown in the preliminary analysis.

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

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

26 **3. Results**

27 **3.1. Participant Characteristics**

28 A total of 41 F and 111 NF elderly individuals participated in the study. The demographic and

1 performance characteristics of participants in both groups are shown in Table 1. Participants in
2 the F group were significantly older than those in the NF group. F participants took significantly longer
3 to complete the WT, TUG, and 5CS tests than NF participants. There were no significant
4 differences in other variables between groups.

6 **3.2. Group Comparisons**

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

13 **3.3. Logistic Regression and ROC Analysis**

14 In the analysis, the measurements that were significantly different between groups (the
15 stepping-response score, age, WT, TUG, 5CS, reaction time, and stepping time) were employed as
16 independent variables. Stepwise logistic regression analysis indicated that the stepping-response
17 score (OR = 0.15; 95% CI = 0.12– 0.51; $p < 0.001$) and 5CS (OR = 1.23; 95% CI = 1.04 – 1.45; $p =$
18 0.015) were the independent variables that remained in the final step of the regression model and
19 were therefore considered to be independently associated with falling (Table 3). The ROC curve
20 had a moderate area under the curve (AUC) for stepping-response score (0.73) and a low AUC for
21 5CS (0.65). The sensitivity of the stepping-response score was 73.0%, and the specificity was
22 69.7%.

24 **4. Discussion**

25 This is the first study using a stepping performance device that integrates temporal and spatial
26 measurements to identify elderly individuals at a risk for falling. Quick step execution (5, 8) and
27 step accuracy (4, 12) are important skills that can serve to alter the support base, preserve stability,
28 and prevent a fall. Our step-tracking device that uses an infrared laser sensor can conveniently

1 assess these components of stepping performance. Previously, a similar portable device that
2 included a dance mat step-timing device was used to easily assess stepping performance
3 parameters (21). Since our new device can also assess stepping performance step speed, length
4 and accuracy, it may be useful for determining fall risk.

5 Similar to previous studies (5-7), the present study showed participants with a history of falls had
6 significantly longer stepping reaction times than those with no history of falls. The
7 stepping-response score we developed that integrates temporal and spatial measurements can
8 discriminate between participants with and without a history of falls with good sensitivity using a
9 logistic regression and discriminant analysis. Avoiding falls in real-life situations requires fast and
10 appropriate step responses, and the speed and accuracy of responses can be indicated by the step
11 speed and accuracy measurements used in the present study. In the results of the present study,
12 there was no significant difference in step accuracy measurement, probably because of the
13 comparatively easy stepping performance tasks. However, formulating a stepping-response
14 score that integrates temporal and spatial measurements was the most reasonable index
15 (preliminary regression analysis) among the candidate indexes (e.g. the model: age and reaction
16 time) and could successfully identify individuals at risk of falling. This may be because step
17 accuracy measurement was related to the risk of falling as an internal factor in our stepping
18 performance task. We will need to investigate this more thoroughly in a future study. Although
19 previous rapid step reaction tests used only step speed as a fall risk indicator for elderly individuals
20 (8, 22), the prevention of falls may require the assessment of multiple aspects of step responses.
21 The stepping-response score in this study is the first index that assesses the risk of falls from the
22 perspective of step speed and accuracy. Moreover, stepping-response score was mildly
23 correlated with motor and cognitive functions (results not shown). Therefore, this
24 stepping-response score is a novel index that assesses fall risk from a new perspective.

25 The new step-tracking device developed is fairly inexpensive and portable in comparison to other
26 step performance assessment tools. These characteristics enable its use at clinical sites.
27 Furthermore, our device does not require specialized personnel, and the difficulty of the stepping
28 task can be adjusted according to the subjects undergoing assessment. For example, we could

1 ask participants to step in a direction contrary to that indicated by the arrow on the computer
2 monitor. Therefore, the device has high utility and can be used in clinical settings or in homes of
3 elderly individuals as both an assessment tool and a training device. Recent intervention studies
4 have indicated that abilities relating to voluntary stepping can be improved by training (23, 24).
5 Elderly individuals are also able to improve their balance under dual task (DT) conditions after
6 specific DT balance training (25, 26). In a previous study, we reported that a rhythmic stepping
7 exercise under cognitive conditions like the task of present study improved DT function (26). This
8 exercise has potential as a means of public health promotion, as it can be performed within a small
9 indoor space. Our device can also serve as a training aid and can be used to facilitate effective
10 exercise at community and clinical sites. A prospective cohort study is needed to further evaluate
11 the relationship between falling incidents and stepping-response score. We hope that our device
12 is not only useful for fall assessment but also opens avenues for developments in
13 cognitive-locomotion science.

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

25 **5. Conclusions**

26 The present study indicates that our new stepping performance device that uses LRF can be an
27 effective clinical tool to identify high risk elderly individuals and the measurements obtained using
28 this device reflect multilateral parameters, such as motor and cognitive functions. The new index

1 we developed that integrates temporal and spatial measurements can successfully discriminate
2 between participants who are at a high and low risk of falling.

3

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6 University for their help with data collection. We would also like to acknowledge Murata Machinery,
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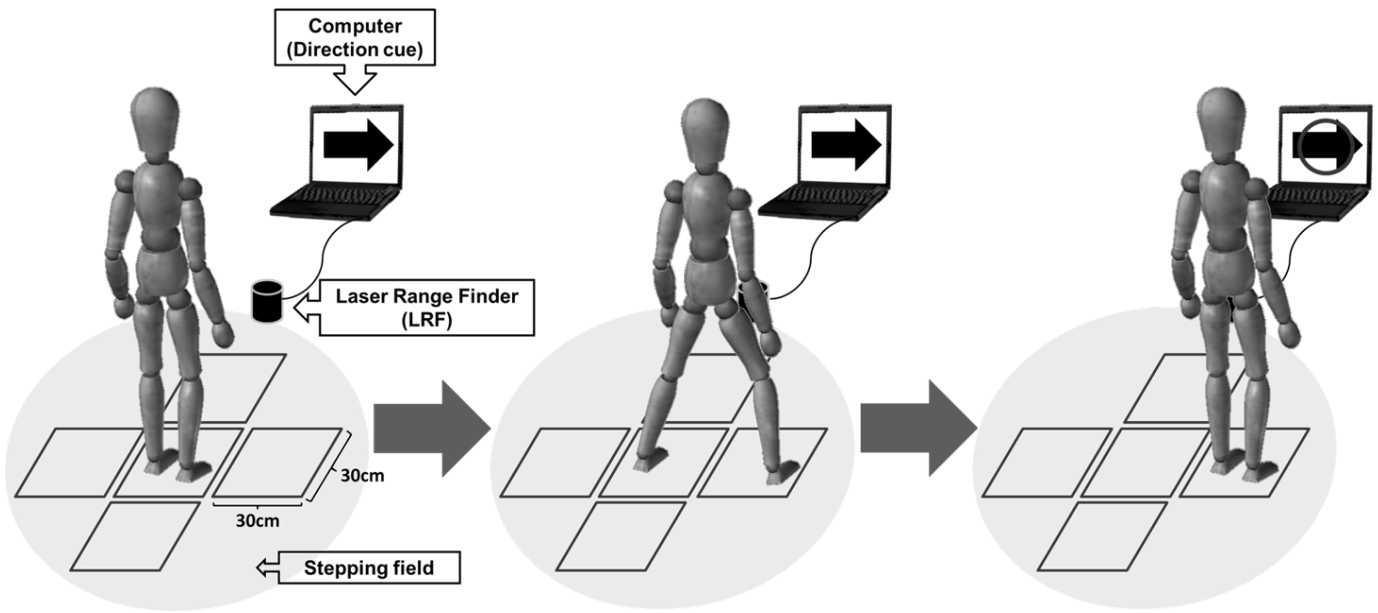
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3 Figure 1. Schematic representation of the step-tracking device and the stepping performance task.
4 The circle represents the stepping field in which the infrared laser sensor can detect the motion of
5 both legs. Participants initially stood upright in the center square of five 30 cm x 30 cm squares
6 arranged in a plus shape. Participants were instructed to quickly step with one leg, followed by the
7 other leg into 1 of the 4 squares arranged around the starting position when provided with a visual
8 cue indicating which direction to step.

9

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)	<i>p</i> -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.

1

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

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

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