Training with a balance exercise assist robot is more effective than conventional training for frail older adults

Kenichi Ozaki,† Izumi Kondo, Satoshi Hirano, Hitoshi Kagaya, Eiichi Saitoh, Aiko Osawa and Yoichi Fujimori

1Department of Rehabilitation Medicine, National Center for Geriatrics and Gerontology, Ohsu, 2Department of Rehabilitation Medicine 1, School of Medicine, Fujita Health University, Toyoake, 3Partner Robot Division, Toyota Motor Corporation, Toyota, Aichi, Japan

Aim: To examine the efficacy of postural strategy training using a balance exercise assist robot (BEAR) as compared with conventional balance training for frail older adults.

Methods: The present study was designed as a cross-over trial without a washout term. A total of 27 community-dwelling frail or prefrail elderly residents (7 men, 20 women; age range 65–85 years) were selected from a volunteer sample. Two exercises were prepared for interventions: robotic exercise moving the center of gravity by the balance exercise assist robot system; and conventional balance training combining muscle-strengthening exercise, postural strategy training and applied motion exercise. Each exercise was carried out twice a week for 6 weeks. Participants were allocated randomly to either the robotic exercise first group or the conventional balance exercise first group. Main outcome measures: preferred and maximal gait speeds, tandem gait speeds, timed up-and-go test, functional reach test, functional base of support, center of pressure, and muscle strength of the lower extremities were assessed before and after completion of each exercise program.

Results: Robotic exercise achieved significant improvements for tandem gait speed ($P = 0.012$), functional reach test ($P = 0.002$), timed up-and-go test ($P = 0.023$) and muscle strength of the lower extremities ($P = 0.001–0.030$) compared with conventional exercise.

Conclusions: In frail or prefrail older adults, robotic exercise was more effective for improving dynamic balance and lower extremity muscle strength than conventional exercise. These findings suggest that postural strategy training with the balance exercise assist robot is effective to improve the gait instability and muscle weakness often seen in frail older adults. Geriatr Gerontol Int 2017; 17: 1982–1990.

Keywords: assistive technology, frailty, postural balance, rehabilitation.

Introduction

Frailty is an age-associated biological syndrome characterized by decreases in biological functional reserve and resistance to stressors as a result of changes in several physiological systems, placing the individual at special risk of poor outcomes (e.g. disability, loss of independence and hospitalization) from minor stressors.1–4 The prevalence of frailty in people aged older than 65 years is 7.2%, increases with age, and represents the main risk factor for incident falls, disability, hospitalization and death.5 The diagnosis of frailty comprises several domains, including weight loss, weakness, exhaustion, slowness and low physical activity.6 In addition, other diseases, such as malnutrition, immobility, anemia, obesity, cancer and cardiovascular disease, can accelerate the morbidity and mortality induced by frailty syndrome.6

The effects of physical exercise in improving the functional capacity of frail older adults have been the focus of recent research.7,8 Exercise programs tailored to this population have been shown to be effective. These interventions, such as resistance training, balance training, endurance training, coordination training and multicomponent exercises, have yielded beneficial effects on certain functional parameters in frail older adults. However, multicomponent exercise programs that include resistance
training appear to result in greater overall enhancements, because this type of intervention stimulates several components of physical health, such as strength, cardiorespiratory fitness and balance. Although some systematic reviews have explored the benefits of exercise in frail older adults, effects of physical activities on frailty remain controversial.9-11 These reviews have applied very broad definitions of frailty that have included both non-frail and prefrail participants.

Some studies have compared different types of exercise. The addition of whole-body vibration to strength and balance exercises failed to show an effect on the timed up-and-go test (TUG) and Berg Balance Scale (BBS).12 Carrying out tai chi was found to significantly reduce the risk of falling compared with conventional physiotherapy, although the mean number of falls did not differ between both groups.13 Balance training using visual computer feedback had no effect on the TUG test, BBS or 6-min walk test compared with conventional balance training.14 Such studies have shown no consistent effect of interventions on performance measures.

In contrast, training with a balance exercise assist robot (BEAR) system is reportedly effective for improving posture strategies of patients with central nervous system disorders.15 This system uses a personal transport assistance robot on which the rider stands, controlled by an inverted pendulum system with two in-wheel-type motors, to move the rider’s center of gravity (COG). Task difficulty can be adjusted using information from the sensing device, including velocity and body gradient. Information from the robot is transmitted to a personal computer to control the robot and provide an appropriate postural task to the rider. To help the rider properly carry out postural strategy training, some games have been designed as exercises against perturbation and for moving the COG. As a result, dynamic balance and lower extremity muscle strength were improved in patients with central nervous system disorder.15 We considered that this training might also prove effective for improving postural strategy and lower extremity muscle strength in the frail older adults. The aim of this research was to examine the effect of this training using the BEAR system on postural strategy, muscle strength and training enjoyment among frail older adults in comparison with conventional physical training.

**Methods**

**Design**

The study was designed as a cross-over trial without a washout term. The clinical research ethics committee in our institution approved the design of this study (No. 558).

**Participants**

From a volunteer sample of community-dwelling older adults who felt that they were becoming frail, 33 participants were recruited for this study. For inclusion criteria, we required volunteers to fulfill the diagnostic criteria for frailty or prefrailty. The Cardiovascular Health Study criteria described by Fried et al. were modified for the present study (Table 1).5 Patients with disturbance of consciousness or communication difficulty, those who had cardiovascular problems limiting the ability to carry out the exercise, or patients with impairments of upper extremity function that would inhibit them from holding the handle of the training instrument were excluded from the study.

Of the 33 prospective participants, one was excluded because the inclusion criteria were not satisfied, one decided to withdraw before randomization and two withdrew because they encountered difficulty in attending the center regularly. Written informed consent was obtained from the remaining 29 participants before participation in the present study.

The 29 participants were randomly divided into two groups: a robotic exercise first group (n = 15), and a conventional exercise first group (n = 14). Both groups had one participant drop out because of exacerbation of underlying chronic diseases. Finally, 27 participants (7 men, 20 women; mean age 73 ± 6 years; range 65–85 years; mean bodyweight 52.4 ± 8.2 kg; 10 frail, 17 pre-frail; mean BBS17 50.3 ± 4.2) completed the study and were analyzed.

| Characteristic       | Definition                                                                 |
|----------------------|-----------------------------------------------------------------------------|
| Weight loss          | Lost >10 pounds unintentionally in past year                                |
| Exhaustion           | Any of: Felt unusually tired in past 2 weeks                                |
|                      | Felt unusually fatigue in past 2 weeks                                      |
| Low activity level   | The lowest quartile in the modified Baecke questionnaire16                  |
| Weakness             | Grip strength of the dominant hand:                                        |
|                      | 30 kg > grip strength in men                                                |
|                      | 20 kg > grip strength in women                                              |
| Slowness             | Walking speed in ≤0.8 m/s                                                    |

Frailty: ≥3 items Prefrail: 1 or 2 items Robust: 0 item Cardiovascular Health Study criteria by Fried et al.5 were modified.
A flow diagram of the progress through the phases of this study is shown in Figure 1.

**Instruments**

The BEAR (Toyota Motor Corporation, Aichi, Japan) used in the current study in the robotic exercise phase had two wheels with in-wheel-type motors, controlled by an inverted pendulum system, as well as two footplates on either side that inclined separately, thereby maintaining a horizontal position when the rider banked the robot laterally (Fig. 2a). The rider stood on the footplates and grasped the handle attached to the center pillar of the robot. The BEAR moved according to the position of the rider’s COG. When the rider leaned forward, the wheel rotated in the same direction and the robot moved forward until the rider’s body returned to a vertical position (Fig. 2b). Conversely, if the rider leaned backward, the robot would move backward. When the rider wished to turn left or right, they either leaned their body or turned the handle of the device to the desired side. During this movement, each wheel rotated in the opposite direction.

To maintain safety during the exercise, we prepared a 2.4-m × 2.0-m space in the exercise room for the exclusive use of the participants. In addition, participants wore a helmet and a suspending device (Fig. 2c).

**Procedures**

Participants were randomly allocated to the robotic exercise first group or conventional exercise first group using a randomization table generated by a blinded statistician. After enrollment, exercises were carried out 24 times during the total intervention period; twice a week for a total of 12 weeks (12 robotic exercises of 6 weeks, 12 conventional exercises of 6 weeks). When the first exercise phase was finished, participants started another exercise phase in the next week.

In the robotic exercise phase, participants carried out an exercise for moving the COG with the BEAR as a tennis game. The BEAR was able to transmit location information to a personal computer using a wireless local area network. In the tennis game, anterior and posterior movements of the BEAR were transformed to up and down movements of the player on the game monitor. Left and right side rotation movements of the BEAR were not reflected to the game. A player moved to the location of the flying ball, and returned the ball. The level of difficulty of the tennis game could be set by altering ball speed automatically. If a participant was able to return the ball beyond the decided rate and precision, the BEAR system increased the level of the game by increasing the speed of the ball. The actual game screen is shown in Figure 2d. One set of exercises consisted of a 2-min warm-up (operation) exercise with the BEAR and six 3-min rounds of exercise moving the COG.

In the conventional exercise phase, participants carried out one-on-one physiotherapy: muscle-strengthening exercises for older adults, such as squat exercise and isotonic exercise using a weight band, and standing posture exercise, such as exercise on a balance board, and movement exercises requiring fine motor control. The preceding study of BEAR gave us the result of improving dynamic balance and lower extremity muscle strength, so these contents were considered to be matched to the robotic
Exercise. One set of exercises consisted of a 2-min warm-up exercise and six 3-min rounds of each conventional exercise (Table 2).

Measurements

Preferred and maximal gait speeds, tandem gait speeds, TUG, functional reach test (FRT), functional base of support, COP, muscle strength of the lower extremities, and grip strength were measured before starting the program and the day after the last session of each exercise. After the exercise, each participant rated whether the exercises had been enjoyable through a questionnaire.

Each test was carried out twice and the best result recorded.

During the measurement of preferred and maximal gait speeds, participants were instructed to walk 14 m twice at a self-selected comfortable walking speed, and twice at a self-selected maximal walking speed. The time and number of steps taken to reach 10 m along the walkway were measured.

During the evaluation of tandem gait, participants were instructed to walk as fast as possible using a tandem stance.

Figure 2  (a) The balance exercise assist robot (BEAR). BEAR is a stand-and-ride transport robot, and a personal mobility device with two inverted wheel motors. Movement is achieved by transferring the rider’s center of gravity. (b) Mechanisms of the BEAR: (1) If the body inclines, (2) the wheels rotate in the same direction. (3) Subsequently, the body returns to a vertical position. On this occasion, the body moves with the rotation of the wheels. (c) Setting a balance exercise with the BEAR. (d) Actual game screen for the BEAR.
The TUG was initially developed as a basic mobility test for older people, and offers good accuracy for identifying frailty.

Participants carried out the FRT twice according to the method proposed by Duncan. Briefly, this test required achieving the maximal distance that the participants can reach forward beyond arm’s length while maintaining a fixed base of support in a standing position.

The functional base of support is one of the dynamic balance tests proposed by King, calculated as the ratio of the difference between the mean COP location on the force platform during sustained forward and backward leaning to foot length. The functional base of support was measured twice using a gravicoder force platform (G-5500; Anima, Tokyo, Japan).

COP, as the index of postural stability, was measured twice using the gravicoder force platform under a 20-Hz sampling rate, 30-s duration, and with the participant’s eyes open and legs together. Total path length, root mean square of area and sway area from the locus of the COP during measurement were assessed.

Strength of hip flexion, hip abduction, knee extension, knee flexion, ankle dorsiflexion and ankle plantar flexion were measured using a hand-held dynamometer (μ-tas F-1; Anima, Tokyo, Japan). Positioning of joints for each measurement followed the methods proposed by Bohannon. Hip flexion was tested in the supine position, with the hip flexed at 90° and the knee relaxed. Hip abduction was tested in the supine position, with the knee extended and the hip in neutral abduction. Knee extension and flexion were tested while sitting, with the knee and hip flexed at 90°. Ankle dorsiflexion and plantar flexion were tested in the supine position, with the hip and knee extended. Grip power was measured using a grip dynamometer. Each strength test was carried out twice and the best result recorded.

The questionnaire regarding enjoyment of the exercise was based on a visual analog scale. Participants were asked to make a mark on a 10-cm line according to how they felt regarding training. The two questions were as follows: “Did you enjoy robotic exercise?” (0 cm = not enjoyed at all, 10 cm = enjoyed very much); and “Which do you like better?” (0 cm = conventional exercise, 10 cm = robotic exercise).

### Statistical analysis

All data were compared using repeated-measures (2 × 2) analysis of variance (ANOVA) to compare principal effects in relation to the interaction between time (before and after) and group (robotic exercise and conventional exercise). All statistical analyses were computed using SPSS version 21.0.0.0 (IBM, New York, NY, USA), with a significance level of \( P < 0.05 \).

### Results

Measurements before and after each exercise and change (Δ) are shown in Table 3. With robotic exercise, significant improvements were observed for dynamic balance ability and muscle strength of the lower extremities compared with conventional exercise. Significant improvements were found in tandem gait speed \((P = 0.012)\), FRT \((P = 0.002)\) and TUG \((P = 0.023)\). Significant increases were also seen in hip abduction \((P = 0.001)\), ankle dorsiflexion \((P = 0.006)\) and plantar flexion \((P = 0.030)\). Conversely, no significant changes were observed in preferred gait speed \((P = 0.117)\), maximal gait speed \((P = 0.378)\), functional base of support \((P = 0.065)\), total path length \((P = 0.337)\), ankle dorsiflexion \((P = 0.065)\), knee extension \((P = 0.196)\), knee flexion \((P = 0.262)\) or grip power \((P = 0.521)\). Pre- and post-score of measurements are shown in Figure 3.

In response to the first question assessing enjoyment of the exercise, “Did you enjoy robotic exercise?”, participants indicated a mean score of 9.1/10.0 cm on the visual analog scale, suggesting high enjoyment. As shown by the mean response to the second question, “Which do you
| Table 3 | Measurements of before, after and changes (delta) each exercise |
|---------|---------------------------------------------------------------|
|         | Robotic exercise | Conventional exercise | Exercise × time |
|         | Before | After | Changes | P-value | Before | After | Changes | P-value | P-value |
| Gait    |         |       |          |         |         |       |          |         |         |
| Preferred gait speeds (m/min) | 80.0 ± 16.2 | 83.1 ± 17.9 | 3.2 ± 9.3 | NS | 82.2 ± 17.5 | 82.1 ± 18.6 | -0.2 ± 6.0 | NS | NS |
| Maximal gait speeds (m/min) | 105.9 ± 24.5 | 110.5 ± 25.0 | 4.5 ± 8.0 | 0.012 | 108.0 ± 24.9 | 110.4 ± 27.9 | 2.3 ± 8.9 | NS | NS |
| Dynamic postural balance |         |       |          |         |         |       |          |         |         |
| Tandem gait speeds (m/min) | 22.2 ± 9.5 | 27.5 ± 9.8 | 5.6 ± 4.9 | < 0.001 | 24.9 ± 10.1 | 26.5 ± 11.6 | 1.6 ± 4.6 | NS | 0.012 |
| FRT (cm) | 28.0 ± 5.3 | 30.8 ± 6.0 | 2.8 ± 2.6 | < 0.001 | 29.3 ± 5.8 | 29.7 ± 5.6 | 0.1 ± 2.6 | NS | 0.002 |
| FBOS (%) | .37 ± .12 | .44 ± .11 | .07 ± .09 | 0.001 | .41 ± .12 | .42 ± .13 | .01 ± .05 | NS | NS |
| TUG (s) | 9.4 ± 4.1 | 8.7 ± 3.2 | -0.7 ± 1.1 | 0.002 | 9.0 ± 3.3 | 8.7 ± 2.8 | -0.3 ± 0.8 | NS | 0.023 |
| Static postural balance (COP) |         |       |          |         |         |       |          |         |         |
| Total path length (cm) | 34.4 ± 12.8 | 37.0 ± 14.7 | 2.6 ± 11.4 | NS | 35.7 ± 11.9 | 35.9 ± 13.1 | 0.2 ± 7.2 | NS | NS |
| Muscle strength (all, N) |         |       |          |         |         |       |          |         |         |
| Hip flexion | 189 ± 55 | 215 ± 57 | 26 ± 25 | < 0.001 | 197 ± 52 | 207 ± 56 | 8 ± 29 | NS | NS |
| Hip abduction | 148 ± 53 | 175 ± 50 | 27 ± 25 | < 0.001 | 157 ± 48 | 160 ± 51 | 1 ± 23 | NS | 0.001 |
| Knee extension | 226 ± 66 | 250 ± 58 | 24 ± 30 | < 0.001 | 237 ± 60 | 250 ± 71 | 10 ± 30 | NS | NS |
| Knee flexion | 127 ± 46 | 145 ± 47 | 18 ± 18 | < 0.001 | 128 ± 45 | 139 ± 49 | 10 ± 20 | 0.010 | NS |
| Ankle dorsiflexion | 217 ± 37 | 235 ± 43 | 18 ± 26 | 0.001 | 227 ± 43 | 225 ± 48 | -2 ± 23 | NS | 0.006 |
| Plantar flexion | 313 ± 112 | 375 ± 115 | 62 ± 36 | < 0.001 | 341 ± 133 | 368 ± 129 | 27 ± 50 | 0.026 | 0.030 |
| Grip | 257 ± 54 | 258 ± 51 | 1 ± 14 | NS | 255 ± 55 | 259 ± 53 | 4 ± 21 | NS | NS |

Data presented as mean ± standard deviation (n = 27). COP, center of pressure; FBOS, functional base of support; FRT, functional reach test; NS, not significant; TUG, timed up-and-go test.
like better?”, participants also favored the BEAR over conventional exercise (8.3/10.0 cm).

Discussion

We carried out the present study to compare the efficacy of BEAR and conventional training for improving postural strategy and muscle strength among frail or prefrail older adults. After each 6-week training session, significant improvements were noted for tandem gait speed, FRT, TUG, and muscle strength around the hip and ankle joint using the BEAR exercise. In contrast, maximal and preferred gait speeds, COP, muscle strength around the knee joint, and grip power did not differ significantly between groups. In addition, participants rated BEAR training as more enjoyable than conventional balance exercises.

In terms of balance ability, we anticipated that all indices would be improved after BEAR training. However, although dynamic balance ability including tandem gait speeds, FRT and TUG were improved after postural strategy training with the BEAR, static balance as represented by the locus of COP remained unimproved. Training specificity is a key element of motor learning. There were no significant associations between different components of balance, such as static/dynamic steady-state balance and reactive balance, it appears that the different balance strategies are independent of each other and need to specifically be addressed during intervention programs. In robotic exercise with the BEAR, participants moved the COG actively. We inferred that there was transferring of training between robotic COG movement and dynamic balance, such as tandem gait, FRT and TUG.

In the present study, the strength of muscles around the ankle and hip joints was improved after training with the BEAR. Hemami et al. suggested that ankle angle was subjected to the largest movement during translational platform perturbation, and that major postural corrections were initiated by the ankle. Van Ooteghem et al. also reported that ankle strategy was the first to develop during translational platform perturbation exercise. In contrast, Hwang et al. suggested that the ankle strategy was used during slow-speed perturbation, whereas a strategy...
involving both ankles and hips was used during fast-speed perturbation.\textsuperscript{27} Older adults have been reported to rely less on the ankle strategy for balance, and as a result require more use of the hip strategy.\textsuperscript{28,29} We assume that moving the COG with the BEAR was effective in improving both ankle and hip strategies, along with strength of the muscles around these joints in frail older adults.

Elements identified in the cycle of frailty are core clinical presentations of frailty, and that a critical mass of phenotypic components in the cycle would be identified as the syndrome.\textsuperscript{30} The main causes of frailty have been thought to be sarcopenia and undernutrition. Instability during standing and walking, and the unfavorable consequence of falls seem to be the results of frailty. However, falls and instability also cause fear of fall-related injuries and decreased activity among frail older adults. As a result of reduced activity, muscle weakness and the more severe sarcopenia can develop. Balance exercises with the BEAR improved not only dynamic balance, but also muscle strength. These changes were attributed to improvement of activity levels, total energy expenditure and undernutrition.

A number of limitations to the present study warrant attention. First, we did not follow up effects on the rate of falls by participants. The BBS score of participants in the present study was not particularly poor (54.3 ± 4.2), so we considered it likely that a large amount of time would be required to determine fall rates. Second, the changing status of frailty in participants was not considered. Whether frail older adults would improve and prefrail older adults would be prevented from becoming frail by continuing the exercises in the present study represents a very interesting issue. We are starting to follow the status of the participants. In addition, the small sample size from a heterogeneous population makes it difficult to generalize our findings. To obtain more valid evidence of the effectiveness of this robotic exercise among frail and prefrail older adults, we are now planning to investigate a larger cohort than in the present study.

Acknowledgments

The authors thank research assistant physical therapists Naoki Itoh, Kenji Satoh and Kazuhiro Hashimoto, and research assistant Naho Hashimoto for cooperation in the robotic exercise study, and Atsushi Toshimi from Toyota Motor Co. Ltd. for cooperation in maintenance of BEAR.

This material has not been previously presented. The authors have no financial support. The authors received the support as leasing a BEAR from Toyota Motor Co. Ltd.

Disclosure statement

The authors declare no conflict of interest.

References

1. Campbell AJ, Buchner DM. Unstable disability and the fluctuations of frailty. \textit{Aging Ageing} 1997; \textbf{26}:315–318.
2. Walston J, Fried LP Frailty and the older man. \textit{Med Clin North Am} 1999; \textbf{83}:1173–1194.
3. Rockwood K, Mitnitski A. Frailty in relation to the accumulation of deficits. \textit{J Gerontol A Biol Sci Med Sci} 2007; \textbf{62}:722–727.
4. Rodríguez Mañas L, Péart C, Mann G et al. Searching for an Operational Definition of Frailty: A Delphi Method Based Consensus Statement. The Frailty Operative Definition–Consensus Conference Project. \textit{J Gerontol A Biol Sci Med Sci} 2012; \textbf{68}:62–67.
5. Fried LP, Tangen CM, Walston J et al. Cardiovascular Health Study Collaborative Research Group. Frailty in older adults: Evidence for a phenotype. \textit{J Gerontol A Biol Sci Med Sci} 2001; \textbf{56}:146–155.
6. Xue Q-L. The frailty syndrome: Definition and natural history. \textit{Clin Geriatr Med} 2011; \textbf{27}:1–15.
7. Villareal DT, Smith GI, Saliba D, Shah K, Mittendorfer B. Regular multicomponent exercise increases physical fitness and muscle protein anabolism in frail, obese, older adults. \textit{Obesity} 2011; \textbf{19}:312–318.
8. Freiberger E, Häberle L, Spiriduso WW, Rixt Zijlstra GA. Long-term effects of three multicomponent exercise interventions on physical performance and fall-related psychological outcomes in community-dwelling older adults: A randomized controlled trial. \textit{J Am Geriatr Soc} 2012; \textbf{60}:437–446.
9. Daniels R, van Rossum E, de Witte L, Kempen GI, van den Heuvel W. Interventions to prevent disability in frail community-dwelling elderly: a systematic review. \textit{BMC Health Serv Res} 2008; \textbf{8}:278.
10. Chou CH, Hwang CL, Wu YT. Effect of exercise on physical function, daily living activities, and quality of life in the frail older adults: a meta-analysis. \textit{Arch Phys Med Rehabil} 2012; \textbf{93}:237–244.
11. Cadore EL, Rodríguez-Mañas L, Sinclair A, Izquierdo M. Effects of different exercise interventions on risk of falls, gait ability, and balance in physically frail older adults: a systematic review. \textit{Rejuvenation Res} 2013; \textbf{16}:105–114.
12. Pochlock RD, Martin FC, Newham DJ. Whole-body vibration in addition to strength and balance exercise for falls-related functional mobility of frail older adults: a single-blind randomized controlled trial. \textit{Clin Rehabil} 2012; \textbf{26}:915–923.
13. Toussignant M, Corivcau H, Roy PM, Desrosiers J, Dubuc N, Hébert R. Efficacy of supervised Tai Chi exercises versus conventional physical therapy exercises in fall prevention for frail older adults: a randomized controlled trial. \textit{Disabil Rehabil} 2013; \textbf{35}:1429–1435.
14. Hagedorn DK, Holm E. Effects of traditional physical training and visual computer feedback training in frail elderly patients. A randomized intervention study. \textit{Eur J Phys Rehabil Med} 2010; \textbf{46}:159–168.
15. Ozaki K, Kagaya H, Hirano S et al. Preliminary trial of postural strategy training using a personal transport assistance robot for patients with central nervous system disorder. \textit{Arch Phys Med Rehabil} 2013; \textbf{94}:59–66.
16. Voorrips LE, Ravelli AC, Dongelmans PC, Deurenberg P, Van Staveren WA. A physical activity questionnaire for the elderly. \textit{Med Sci Sports Exerc} 1991; \textbf{23}:974–979.
17. Berg KO, Wood-Dauphiné SL, Williams JL, Gayton D. Measuring balance in elderly: preliminary development of an instrument. \textit{Physiother Can} 1989; \textbf{41}:304–311.
18. Duncan PW, Weiner DK, Chandler J, Studenski S. Functional reach: a new clinical measure of balance. \textit{J Gerontol} 1990; \textbf{45}:M192–M197.
19. King MB, Judge JO, Wolfson L. Functional base of support decreases with age. *J Gerontol* 1994; **49**: M258–M263.

20. Podsiadlo D, Richardson S. The timed ‘Up & Go’: a test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc* 1991; **39**: 142–148.

21. Savva GM, Donoghue OA, Horgan F, O’Regan C, Cronin H, Kenny RA. Using timed up-and-go to identify frail members of the older population. *J Gerontol A Biol Sci Med Sci* 2012; **8**: 441–446.

22. Bohannon RW. Hand-held dynamometry; stability of muscle strength over multiple measurements. *Clin Biomech* 1987; **2**: 74–77.

23. Magill RA. *Motor Learning and Control: Concepts and Applications*, Vol. **11**. New York: McGraw-Hill, 2007.

24. Granacher U, Muchlbauer T, Zahner L, Gollhofer A, Kressig RW. Comparison of traditional and recent approaches in the promotion of balance and strength in older adults. *Sports Med* 2011; **41**: 377–400.

25. Hemami H, Barin K, Pai YC. Quantitative analysis of the ankle strategy under translational platform disturbance. *IEEE Trans Neural Syst Rehabil Eng* 2006; **14**: 470–480.

26. Van Ooteghem K, Frank JS, Allard F, Buchanan JJ, Oates AR, Horak FB. Compensatory postural adaptations during continuous, variable amplitude perturbations reveal generalized rather than sequence-specific learning. *Exp Brain Res* 2008; **187**: 603–611.

27. Hwang S, Tae K, Sohn R, Kim J, Son J, Kim Y. Ann. The balance recovery mechanisms against unexpected forward perturbation. *Biomed Eng* 2009; **37**: 1629–1637.

28. Liaw MY, Chen CL, Pei YC, Leong CP, Lau YC. Comparison of the static and dynamic balance performance in young, middle-aged, and elderly healthy people. *Chang Gung Med J* 2009; **32**: 297–304.

29. Lin SI, Liao CF. Age-related changes in the performance of forward reach. *Gait Posture* 2011; **33**: 18–22.

30. Fried LP, Walston J. Frailty and failure to thrive. In: Hazzard WR, Blass JP, Ettinger WH Jr et al., eds. *Principles of Geriatric Medicine and Gerontology*. New York: McGraw Hill, 1998; 1387–1402.