Longitudinal evaluation of balance quality using a modified bathroom scale: usability and acceptability

Jacques Duchêne and David J Hewson

ICD-LM2S UMR CNRS 6279, Université de Technologie de Troyes, France

Summary

We adapted a commercial bathroom scale in order to acquire the raw data from the weight sensors and then to send them to a server via a mobile phone. We investigated the usability and acceptability of the device in a long-term experiment with 22 elderly users that produced more than 5000 weight recordings. Four basic variables were extracted from the vertical force measurements and the stabilogram. The technology was accepted unreservedly, presumably because it did not differ from devices usually encountered in the home. The quantitative results showed a high variability of day-to-day measurement, which was countered by taking a moving average. A balance index was able to identify changes in balance over time. The preliminary results appear promising.

Introduction

Frailty is a geriatric syndrome that results from functional decline in multiple physiological systems, which increase vulnerability to adverse outcomes.[1] The problem is estimated to occur in 7% of elderly people and 40% of the very elderly (>80 years old). There is currently no standard tool to quantify frailty, although a phenotype of physical frailty has been proposed.[1] The underlying risk factors for frailty include cognitive, socio-demographic, biomedical, functional and affective components, as well as the physical features identified by Fried *et al.*[1] One of the core components of frailty is impaired balance[2] which results in an increased risk of falling.

A number of clinical assessment tools are commonly used to provide information related to the increased risk of falls. These tools include the Tinetti test,[3,4] the Timed Get Up and Go test,[5] the Berg Balance Scale[6,7] and the the single-leg balance test.[8] However, such tests are limited in precision, are observer dependent and are applicable only under clinical conditions, usually with a prolonged period of time between successive evaluations. Measures based on Centre of Pressure (CoP) displacement are considered to be the gold standard measure of balance.[9] Some of these CoP measurements have been shown to be well correlated with clinical tests,[10] while others have a more moderate correlation.[11] The main drawback of such biomechanical reference measurements is the need for expensive force plates for tests conducted in laboratories. We have therefore adapted an inexpensive device that is often found in the home: the bathroom scale, much like the adaptation by other authors of a Nintendo Wii balance board.[12] The aim of the present study was to investigate the usability and acceptability of the device to elderly users.

Methods

The device was based on a commercial bathroom scale (PP 3019, Téfal Atlantis, Groupe SEB, Ecully, France). The scale has four force sensors located at its four corners to calculate body weight. The bathroom scale was modified by the manufacturer to provide access to the raw data produced by the sensors, and to function according to the protocol described below. In addition, an infrared sensor was included in the scale in order to detect the presence of the person to be tested, without requiring action from them to start the initialization process. A Bluetooth module was added to provide communication between the device and a local receiver. The local receiver could be a mobile phone or a PC. Data are sent to the receiver after the weighing process has been completed. The local receiver sends the data in a coded format, along with identification information, to a remote server for storage. The data can then be accessed by suitably authorized people.

If it was mass-produced, the device would probably cost less than US$100.

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Correspondence: Jacques Duchêne, ICD-LM2S, Université de Technologie de Troyes, 12 rue Marie Curie, BP 2060, 10010 Troyes cedex, France (*Fax: +33 325 718 554; Email: jacques.duchene@utt.fr*)

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Signal acquisition

The sampling frequency imposed by the scale manufacturer was 16 Hz, which was low compared to previous recommendations.[13] The signals provided by the sensors were the vertical forces applied at each of their locations, i.e. the CoP was estimated as the position of the barycentre of these forces, yielding a 'stabilogram'. The subject's weight was calculated as the sum of the four vertical forces produced by the sensors (Figure 1).

Protocol

Twenty-two elderly subjects (4 males, 18 females) participated in the study. Their mean age was 77 years (SD 5). Exclusion criteria were severe handicaps, acute pathologies or current treatment for any physical injury. Each participant volunteered and signed an informed consent form. The study was approved by the appropriate ethics committee.

During the month prior to the start of the home-based balance assessment, each participant was given a geriatric evaluation, which included the One-leg Balance test, the Tinetti test, the Timed Get Up and Go test, and the Stop Walking when Talking test, as well as tests for cognitive state and depression. This geriatric evaluation was repeated each month for the duration of the experiment. For each subject, the experiment was scheduled to last one year, including possible interruptions (e.g. holidays, trips) while subjects were free to leave the protocol at any time.

The prototype version of the modified bathroom scale was not optimized with respect to energy consumption, so that all subjects were visited each week to ensure that the battery was recharged. These visits, which were much appreciated by the subjects, need to be taken into account when interpreting the results, due to their possible influence on the overall quality of life, which might indirectly affect the number of falls.

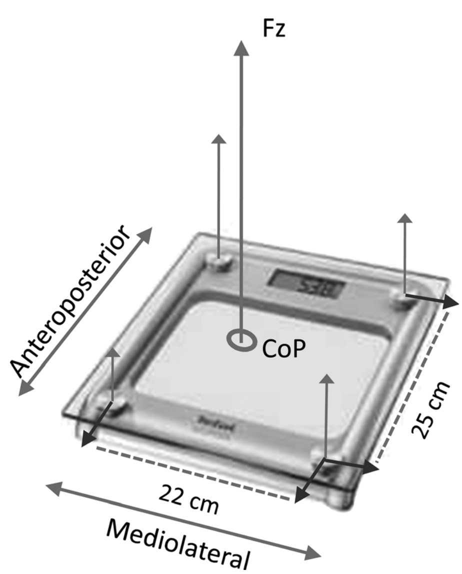

Figure 1 Modified bathroom scale

Protocol rules

Subjects were requested to weigh themselves every morning. The protocol was:

(1) Stand in front of the scale, thus triggering the infrared detector;
(2) Wait for the scale to display '0.0';
(3) Step onto the scale;
(4) Wait for the scale to display the body weight;
(5) Step off the scale.

Although no specific position of the feet was required, the relatively small size of the scale (320 x 295 mm) did not allow for much variation in position. Likewise, no specific position was specified for the head, after preliminary trials had shown that everybody looked down at the display, waiting for the weight value to be displayed.

Activation of the scale was achieved by the infrared sensor. This took about 3s before '0.0' was displayed, which was taken as the starting point of data recording. The subject stepping onto the scale was detected using a threshold of 5 N, which started a timer. At the end of the 10-s timing period, the scale displayed the weight and kept recording until the end of the stepping off phase, which was calculated as the moment when the same 5 N threshold was crossed. The stages of data recording are summarised in Figure 2. The communication process began as soon as data acquisition was completed, using a standard Bluetooth protocol. The scale returned to a standby mode once the communication had been completed successfully, ready for the next measurement.

Checks were also included in the scale software in order to identify any errors due to misuse of the device, or the absence of the local receiver.

Calculated variables

Four variables were calculated, two from the CoP signal and two from the vertical force measurements (Fz).

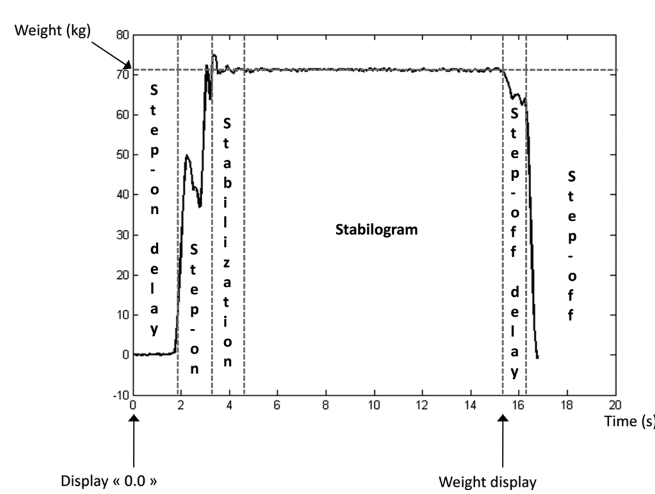

Figure 2 The successive stages of the weighing process

Vertical force

(1) The time delay between the end of the initialization process (when ‘0.0’ was displayed by the scale) and the moment when the subject stepped onto the scale (defined as Fz reaching 10% of the final weight value)
(2) The rise rate (defined as the average slope between 10% and 90% of the final weight value). This variable integrates all hesitations between the first contact of the first foot with the scale and the final phase of the contact of the second foot. It specifically expresses hesitations related to moving the second foot, thus creating inflexions or even peaks in the Fz rising phase.

CoP trajectory

(1) The stabilogram surface area was estimated as the product of the SD of the CoP displacement in the anteroposterior and mediolateral directions, after excluding the step on and step off segments. The surface was standardized by multiplying the surface area by 4π, roughly approximating an ellipse. Intuitively, this variable expresses the level of stability during the static phase, taking into account both anteroposterior and mediolateral oscillations.
(2) The average velocity of the trajectory, which was computed as the sum of the lengths of the successive sample segments, divided by the stabilogram duration. This variable (equivalent to the CoP path length in a fixed time interval) is known as a relevant measure of standing balance.[13]

Usage and acceptability

A questionnaire was given to all subjects, which asked about usage and acceptability. It was based on questions from the European network for Health Technology Assessment (EUnetHTA)[14] and a French questionnaire.[15] The EUnetHTA questions were translated into French. The categories of questions concerned: (1) information quality related to the installation and use of the technology; (2) technology unobtrusiveness; (3) impact of the technology on the user’s habits. In addition, quantitative data were computed about the variability in the time at which subjects weighed themselves, the percentage of days without measurements and the percentage of subjects leaving the protocol before the end of the study.

Results

Usage

There were no concerns about the acceptability of the device in the social environment of the subjects. A bathroom scale located in a bathroom is obviously natural, as was the presence of a mobile phone at home. No subjects complained about the risk of stepping onto the scale, and no problem related to balance due to stepping on and off the scale was reported. Only one subject complained about a lack of precision in the information provided, believing that the device became their property at the end of the experiment. This subject left the study.

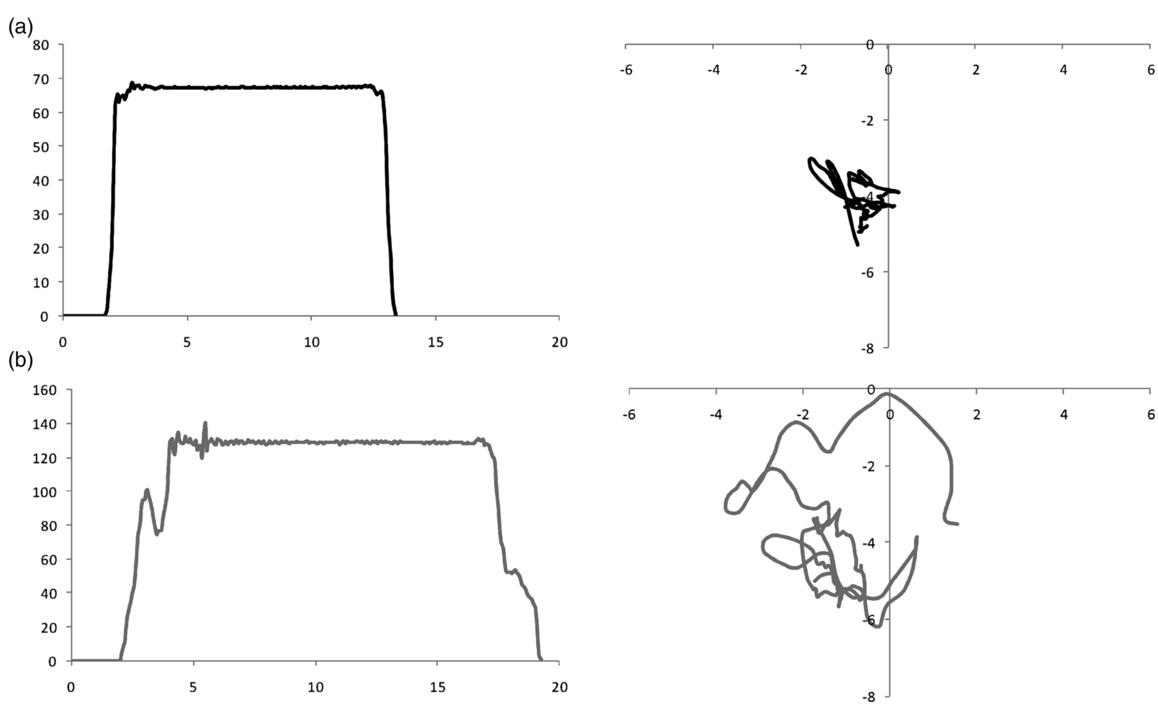

Figure 3 An illustration of the vertical force measurements (left) and the stabilogram (right). For vertical force, the x-axis represents time (s) and the y-axis represents weight (kg). For the stabilogram, the x- and y-axes represent displacement (cm). Data for two cases are shown: (a) subject 8, with no balance problems; (b) subject 3, with precarious balance (confirmed by clinical tests)

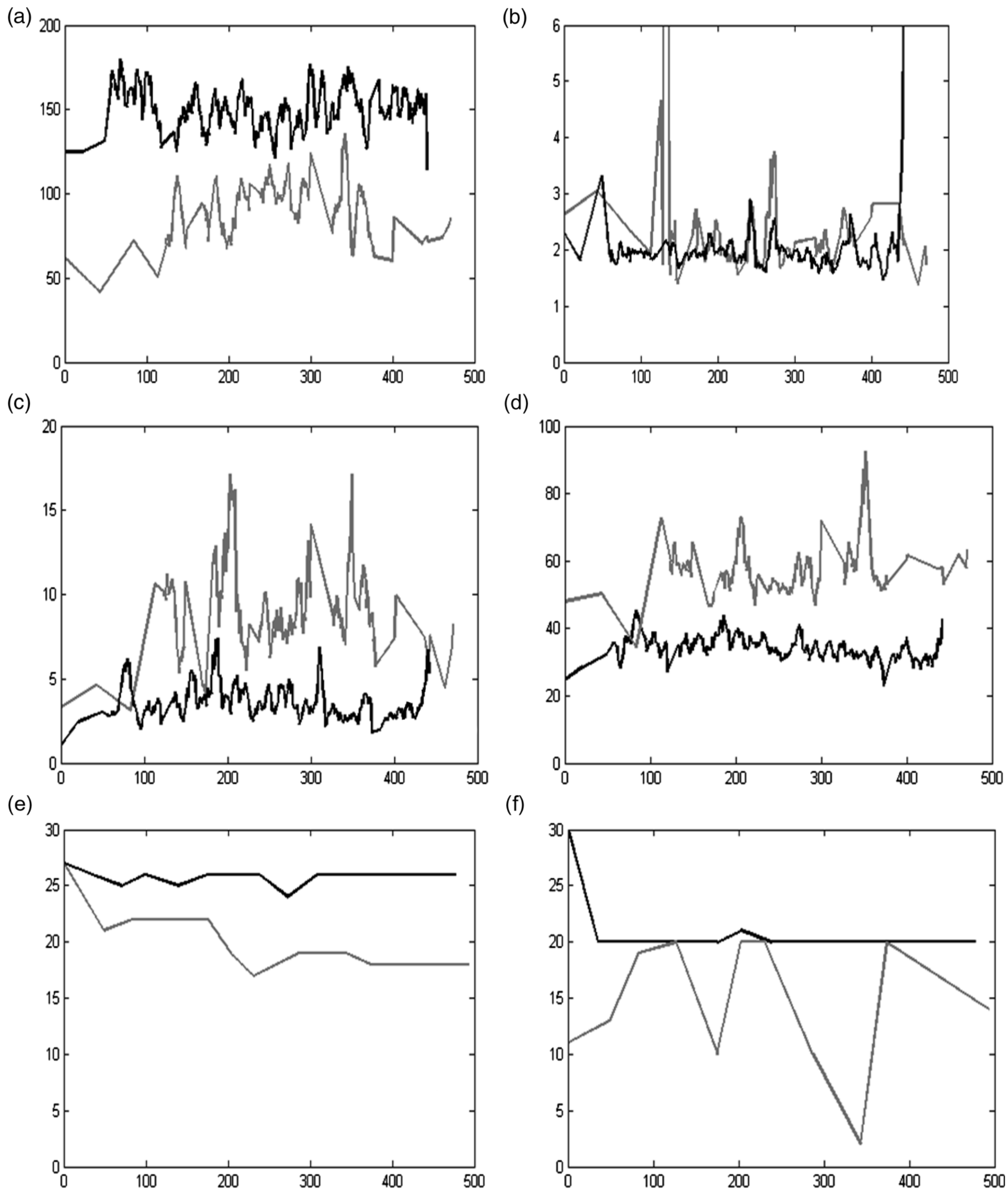

Figure 4 Example of same two subjects as Figure 3. The black line is subject no 8 and the grey line is subject no 3. (a) rising rate (kg/s); (b) delay before stepping on (s); (c) stabilogram mean surface area (cm^2); (d) stabilogram average velocity (cm/s); (e) Tinetti score; (f) one-leg balance (s). The x-axis represents time (days)

The instruction to the subjects to weigh themselves in the morning and at about the same time each day during the whole experiment was broadly respected. The average time at which they weighed themselves was 08:20 (SD 70 min), with two exceptions. One subject made the measurements alternately in the morning and late afternoon and some measurements were made by the investigator who brought a scale to the home of one subject, hence producing very variable measurement times.

The instruction to complete the weighing process every day was followed. The average time interval between two successive measurements was 1.4 days (SD 0.5), if data from one subject living in an area where telecommunications were very poor is discounted.

Among the 22 subjects, four left the protocol before the end of the study (18%). Two left due to weariness (the protocol was thought to be too long), one due to lack of interest and one due to the lack of a perceived direct benefit (possibly a lack of explanation about the blind aspect of the evaluation).

Two main technical limitations were observed during the study. In one case there were telecommunication problems, i.e. some areas in the countryside were badly served, so that communication between the mobile phone and the remote server was sometimes impossible (one subject). In another case the bathroom scale had been placed on a floor covered by a carpet, producing worthless results.

Signals

More than 5000 recordings were transmitted to the database on the server, each of them corresponding to the

Table 1 Coefficients of variation (i.e. ratio of SD to mean) of the variables extracted from the signals

Subject	Delay before step-on	Rising rate	Stabilogram surface	Trajectory velocity
1	0.19	0.25	0.58	0.27
2	0.51	0.37	0.72	0.41
3	0.35	0.23	0.47	0.20
4	0.27	0.21	0.65	0.22
5	0.45	0.16	0.54	0.22
6	0.48	0.16	0.50	0.19
8	0.39	0.23	0.47	0.20
9	0.55	0.23	0.73	0.28
10	0.36	0.20	0.57	0.24
11	0.31	0.17	0.6	0.27
12	0.50	0.15	0.58	0.24
13	0.17	0.19	0.56	0.19
15	0.22	0.23	0.56	0.25
19	0.38	0.19	0.90	0.44
23	0.41	0.15	0.57	0.17

acquisition of the four raw signals produced by the sensors during the weighing process. The Fz force and the stabilogram were then computed and produced the variables as described above. Two examples of tracings are presented in Figure 3, one related to a subject without any balance problems (Figure 3a), the other for a subject presenting severe limitations in mobility (Figure 3b), attested by both a heavy weight and the clinical tests. The evolution of the four variables in these two subjects is shown in Figure 4. Each point is the result of an averaging for a one-week period. Straight-line segments in the tracings indicate that no measurement was obtained during that period of time. This can be seen clearly at the beginning of the study when measurements were made by the investigator, as described previously. The evolution of two clinical variables (Tinetti and One-leg balance) is also shown in Figure 4.

Day-to-day variation of the four calculated variables was assessed by computing a global coefficient of variation as the average of the coefficients of variation calculated within each successive week. The results are shown in Table 1 for all subjects, except for those who did not weigh in regularly or did not produce a sufficient number of readings.

A tentative scoring system was established to produce an index combining the four variables extracted from the sensor signals. The construction of this score (Table 2) was somewhat arbitrary. The scores obtained from subject 3 (grey tracing), and subject 8 (black tracing), are compared in Figure 5. Finally, the results for a patient with multiple pathologies who had a stay in hospital and a fall during the study are shown in Figure 6.

Table 2 Scoring of the four calculated variables

Score value	Delay before step-on (s)	Rising rate (kg/s)	Stabilogram surface (cm^2)	Trajectory velocity (cm/s)
0	≥6	<60	≥12	≥80
1	5, <6	60, <80	8, <12	60, <80
2	4, <5	80, <100	5, <8	40, <60
3	3, <4	100, <120	3, <5	30, <40
4	<3	≥120	<3	<30

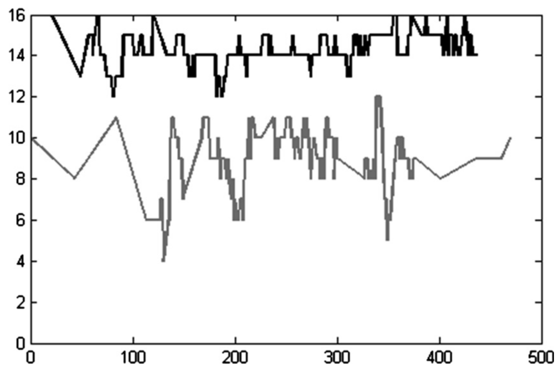

Figure 5 Scores in the same two subjects as Figure 3 and 4. The black line is subject no 8 and the grey line is subject no 3. The y-axis is the score (max = 16). The x-axis represents time in days

Discussion

User perceptions

The bathroom scale provided users with their body weight. The only constraints expressed by some users were the need to weigh themselves every day and to see their weight displayed every day. This was part of the study protocol but should be taken into account for routine follow-up.

Quantitative results

The first lesson to be drawn from the results is that the basic variables extracted from the sensor signals, as described in the present study, cannot be used individually, but they need some averaging before becoming relevant. However, this limitation is not incompatible with future improvements in several ways, such as:

(1) The static part of the measurement, defining the stabilogram, is roughly segmented, meaning that the first part of the stabilogram can be widely influenced by the position of its first point, as shown by the high

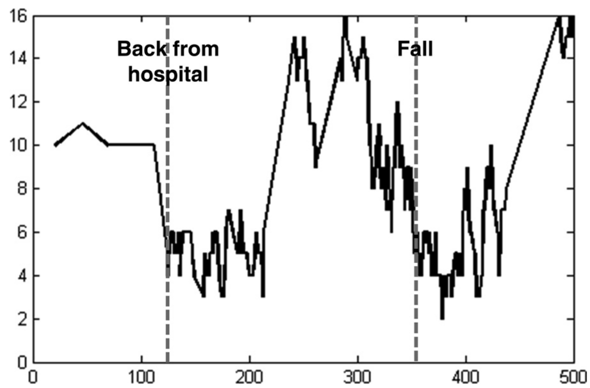

Figure 6 Case-study of a subject with two relevant events during the study (subject no 2). The y-axis is the score (max = 16). The x-axis represents time in days

values of the coefficient of variation related to the stabilogram surface.

(2) Many characteristics of the signal are not exploited, specifically due to the poor sampling frequency imposed by the commercial device. A new generation of device would overcome this problem and allow computation of additional variables that could make sense for stabilogram characterization. One of the future research directions is oriented towards *ad hoc* decomposition methods.

Longitudinal follow-up of balance

The score was constructed empirically. However, a 'Gold Standard' balance score is perhaps an unrealistic aim, since clinical tests of balance show only limited agreement between themselves. A major finding of the present study was the capacity of the balance index to identify changes in balance over time. In the example presented in Figure 6, the subject had a balance index of 10 prior to hospitalization, and the value fell to about five during the 100 days after hospitalization. The subject then recovered somewhat, reaching a balance level of 14 for two months. It is at this point on the graph (280 days) that the potential value of the device can be seen. The subject suffered a systematic decrease in balance quality over the course of nearly three months, finally reaching a value of two. During this time the subject experienced a fall, after two months of continuous decline in balance quality, when the index was seven. It seems likely that the device could be used to identify the increased risk of falling during this two-month period. However, it is still too early to come to any firm conclusions related to such a use of the device in this area.

Finally, it seems likely that the use of the device will require an initial period whereby baseline data are gathered (learning phase), before any deviation during the follow-up period can be detected (surveillance phase). The length of time required for the baseline data should be at least one week.

Conclusion

A modified bathroom scale was tested in the usual environment of elderly users. The technology was accepted unreservedly, presumably because it did not differ from devices usually encountered in the home. Usability was not a concern, due to the very simple utilization procedure. Although a few people dropped out before the end of the study, most subjects spent more than one year in the study without complaining in any way. The quantitative results, although clearly needing improvement, are very promising.

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References

1 Fried LP, Tangen CM, Walston J, *et al*. Frailty in older adults: evidence for a phenotype. *J Gerontol A Biol Sci Med Sci* 2001;**56**:M146–56
2 Fried LP, Hadley EC, Walston JD, *et al*. From bedside to bench: research agenda for frailty. *Sci Aging Knowledge Environ* 2005;**2005**:pe24
3 Tinetti ME. Performance-oriented assessment of mobility problems in elderly patients. *J Am Geriatr Soc* 1986;**34**:119–26
4 Tinetti ME, Speechley M, Ginter SF. Risk factors for falls among elderly persons living in the community. *N Engl J Med* 1988;**319**:1701–7
5 Mathias S, Nayak US, Isaacs B. Balance in elderly patients: the "get-up and go" test. *Arch Phys Med Rehabil* 1986;**67**:387–9
6 Tsang WW, Hui-Chan CW. Effects of tai chi on joint proprioception and stability limits in elderly subjects. *Med Sci Sports Exerc* 2003;**35**:1962–71
7 Shumway-Cook A, Baldwin M, Polissar NL, Gruber W. Predicting the probability for falls in community-dwelling older adults. *Phys Ther* 1997;**77**:812–9
8 Vellas BJ, Wayne SJ, Romero L, Baumgartner RN, Rubenstein LZ, Garry PJ. One-leg balance is an important predictor of injurious falls in older persons. *J Am Geriatr Soc* 1997;**45**:735–8
9 Haas BM, Burden AM. Validity of weight distribution and sway measurements of the Balance Performance Monitor. *Physiother Res Int* 2000;**5**:19–32
10 Tsang WW, Hui-Chan CW. Sensorimotor control of balance: a Tai Chi solution for balance disorders in older subjects. *Med Sport Sci* 2008;**52**:104–14
11 Tsang WW, Hui-Chan CW. Effects of exercise on joint sense and balance in elderly men: Tai Chi versus golf. *Med Sci Sports Exerc* 2004;**36**:658–67
12 Clark RA, Bryant AL, Pua Y, *et al*. Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance. *Gait Posture* 2010;**31**:307–310
13 Salavati M, Hadian MR, Mazaheri M, *et al*. Test-retest reliability [corrected] of center of pressure measures of postural stability during quiet standing in a group with musculoskeletal disorders consisting of low back pain, anterior cruciate ligament injury and functional ankle instability. *Gait Posture* 2009;**29**:460–4
14 Leung DPK, Chan CKL, Tsang HWH, Tsang WWN, Jones AYM. Tai Chi as an intervention to improve balance and reduce falls in older adults: a systematic and meta-analytical review. *Altern Ther Health Med* 2011;**17**:40–48
15 Smulders E, Weerdesteyn V, Groen BE, *et al*. Efficacy of a short multidisciplinary falls prevention program for elderly persons with osteoporosis and a fall history: a randomized controlled trial. *Arch Phys Med Rehabil* 2010;**91**:1705–11