Journals of Gerontology: Medical Sciences
cite as: *J Gerontol A Biol Sci Med Sci*, 2018, Vol. 73, No. 9, 1222–1228
doi:10.1093/gerona/gly077
Advance Access publication 16 April 2018

Research Practice

A Reactive Balance Rating Method That Correlates With Kinematics After Trip-like Perturbations on a Treadmill and Fall Risk Among Residents of Older Adult Congregate Housing

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Received: July 6, 2017; Editorial Decision Date: March 21, 2018

Decision Editor: Anne Newman, MD, MPH

Abstract

Background: A growing number of studies are using modified treadmills to train reactive balance after trip-like perturbations that require multiple steps to recover balance. The goal of this study was thus to develop and validate a low-tech reactive balance rating method in the context of trip-like treadmill perturbations to facilitate the implementation of this training outside the research setting.
Methods: Thirty-five residents of five senior congregate housing facilities participated in the study. Participants completed a series of reactive balance tests on a modified treadmill from which the reactive balance rating was determined, along with a battery of standard clinical balance and mobility tests that predict fall risk. We investigated the strength of correlation between the reactive balance rating and reactive balance kinematics. We compared the strength of correlation between the reactive balance rating and clinical tests predictive of fall risk with the strength of correlation between reactive balance kinematics and the same clinical tests. We also compared the reactive balance rating between participants predicted to be at a high or low risk of falling.
Results: The reactive balance rating was correlated with reactive balance kinematics (Spearman's rho squared = .04–.30), exhibited stronger correlations with clinical tests than most kinematic measures (Spearman's rho squared = .00–.23), and was 42%–60% lower among participants predicted to be at a high risk for falling.
Conclusion: The reactive balance rating method may provide a low-tech, valid measure of reactive balance kinematics, and an indicator of fall risk, after trip-like postural perturbations.

Keywords: Balance-biomechanics, Exercise, Falls, Gait-biomechanics

Among adults 65 and older, falls are the leading cause of nonfatal injuries treated in emergency departments (1). An important behavioral response for preventing falls is a reactive stepping response after a large postural perturbation to expand and re-establish the base of support. In fact, a number of studies have investigated training that promotes effective stepping as a fall prevention exercise intervention among older adults. Okubo and colleagues performed a meta-analysis of 16 studies of step training and reported that such training reduced falls by ~50% among older adults. This reduction was attributed to improvements in reaction time, gait speed, standing balance, and reactive balance recovery (2). Mansfield and colleagues performed a meta-analysis of eight studies of perturbation-based balance training that involved reactive stepping responses to sudden postural perturbations, and reported a reduction in the number of fallers (risk ratio = 0.71) and falls (rate ratio = 0.54) compared with controls (3).

Several intervention studies have used modified treadmills to impose trip-like perturbations (forward loss of balance) to train the reactive balance response that involves multiple steps to regain balance and re-establish stable gait (4–11). This focus on trip-like perturbations is motivated by the large percentage of trip-induced falls among community-dwelling older adults (12,13) and the "specificity of training" principle (14). Common outcome measures used in these intervention studies include trunk and stepping kinematics (5,10,11) as assessed using a motion capture system. In particular, trunk angle and angular velocity (5,10,11) and step length (5,11) have been used based on their differences between successful and failed recoveries after trip-like perturbations (11). As this type of training becomes more prevalent, it would be helpful to have a more "low-tech" and accessible method to assess reactive balance (ie, without the need for a motion capture system). Low-tech methods exist to assess balance after waist-pull perturbations (15–17), brief treadmill translations (18), or manual perturbations (19). However, we are not aware of any such methods that can be applied to treadmill perturbations that require many steps to avert a fall and establish a stable gait pattern. Moreover, a method that encompasses multiple components of the reactive response to trip-like perturbations (such as trunk and stepping responses) may better characterize an individual's overall performance and fall risk than specific kinematic measures that only focus on a single component.

The goal of this study was thus to develop and validate a low-tech reactive balance rating (RBR) method in the context of trip-like treadmill perturbations. We propose RBR as a method to assess two separate but related constructs of reactive balance performance and fall risk, which can be used in the context of trip-like treadmill perturbations. To evaluate the concurrent validity of RBR with respect to reactive balance performance, we hypothesized that RBR would be correlated with reactive balance kinematics. If so, this would support RBR as a low-tech surrogate measure of reactive balance kinematics and reactive balance performance. To evaluate the concurrent validity of RBR with respect to fall risk, two analyses were performed. We compared the correlations between RBR and clinical tests that predict fall risk, with the correlations between reactive balance kinematics and the same clinical tests. We also compared RBR between participants predicted to be at high risk or low risk for falls using the same clinical tests. We hypothesized that the correlations between RBR and clinical tests would be stronger than the correlations between reactive balance kinematics and the same clinical tests. We also hypothesized that RBR would be lower among participants predicted to be at high risk for falls compared with those predicted to be at low risk. If so, this would support RBR as an indicator of fall risk. If validated, RBR may provide a low-tech, valid measure to assess reactive balance kinematics, and an indicator of fall risk, after trip-like postural perturbations on a treadmill.

Methods

Participants

Thirty-five independent-living residents of five senior congregate housing facilities completed the study (Table 1). Consistent with similar congregate housing cohorts, mean age was 82 years and mean performance on a number of measures suggested borderline elevated fall risk. One fifth of the cohort admitted to fall injury or two or more falls in the past year, indicating a subcohort that would be considered at higher fall risk and eligible for more comprehensive fall risk assessment. Participants were recruited for a randomized controlled trial comparing reactive balance training versus Tai Chi, with the baseline data presented here. Inclusion criteria required participants to (a) be at least 70 years old; (b) walk without the aid of an assistive device; (c) have a bone mineral density of the proximal hip of *t* greater than equal to −2.0, obtained from Dual-Energy X-ray Absorptiometry (Hologic Inc., Hologic Discovery W QDR series, Waltham, MA); (d) score at least 24 on the standardized mini-mental state exam (20); (e) pass a medical screening by a physician that excluded individuals with major unstable cardiopulmonary disease, or other progressive or unstable medical condition that could account for possible imbalance and falls; and (f) not have participated in Tai Chi classes. Recruitment methods included oral presentations at the housing facilities, flyers posted at these facilities, and word of mouth among residents and staff of these facilities. A total of 151 participants expressed initial interest, and 116 participants were excluded because they did not satisfy all inclusion criteria, declined to participate, or had other personal circumstances that precluded their participation. This study was approved by the university Institutional Review Board, and written consent was obtained from all participants prior to participation.

Table 1. Participant Demographic Information, Clinical Tests, and Fall History

Number of participants (women)	35 (24)
Age (y)	81.7 (5.5)
Body mass index (kg/m^2)	29.6 (5.0)
Timed-up-and-go test (s)	13.8 (5.3)
Unipedal stance time (s)	4.9 (5.2)
Maximum step length (in)	19.4 (5.5)
Berg Balance Scale	46.0 (5.1)
Performance-Oriented Mobility Assessment	23.3 (3.2)
Activities-specific Balance Confidence Scale (%)	75 (15)
"Have you fallen and hurt yourself in the past year?" (% yes)	17%
"Have you fallen 2 or more times in the past year?" (% yes)	20%

Note: Data are mean (*SD*) unless otherwise noted.

Reactive Balance Rating

RBR was developed to quantify performance in response to trip-like postural perturbations on a modified treadmill. These perturbations involve a sudden change in treadmill belt speed, from zero to an operator-selected walking speed. A sudden backward movement of the treadmill belt pulls the feet posteriorly and induces a forward loss of balance similar to a trip while walking. An individual's reactive balance response to these perturbations, similar to an actual trip while walking, typically involves stepping to expand the base of support, and a neuromuscular response to minimize trunk flexion. RBR was intended to quantify the effectiveness of this reactive balance response, with three specific goals. First, it should require minimal technical resources and training for the evaluator. Second, it should provide sufficient content validity in that it assesses the multiple aspects of reactive balance important for preventing a fall after trip-like perturbations (ie, stepping and trunk control). Third, it should be able to quantify a wide range of performance.

To accomplish these goals, an RBR testing method was designed to involve six treadmill perturbations, including two at each of three speeds (ie, three levels of difficulty). The RBR rating procedure utilized video recordings of these six perturbations. For each perturbation, the overall reactive response was rated on a three-point scale (0, 1, or 2), using a rubric based on (a) quality of the stepping response and (b) the amount of harness or spotter support (which is related to trunk control). These ratings were then summed across the six perturbations to arrive at an RBR that had possible scores of 0 (worst) to 12. The application of a simple, three-point rating scale for each perturbation limits the amount of training required by raters. The assessment of two aspects of reactive balance (stepping response and support) provides content validity. The use of two perturbations at each of three levels of difficulty provides the ability to identify performance differences between low and high performers. Two backward loss of balance perturbations were also included in the testing protocol to minimize anticipation of perturbation direction, but were not included in the calculation of the RBR.

The RBR testing method used a treadmill (Freemotion 800, Freemotion Fitness, Logan, UT) that was customized to elicit sudden (~ 40 ms) changes in belt speed from zero to a user-selected speed. Similar equipment is available that does not require customization (ActiveStep, Simbex, Lebanon, NH) to elicit these trip-like perturbations. Each of the eight perturbations in the RBR testing protocol involved accelerating the belt in the following direction and to the following speeds in a fixed order: twice posteriorly to 0.8 mph, once anteriorly to 0.5 mph, twice posteriorly to 1.6 mph, once anteriorly to 0.5 mph, and twice posteriorly to 2.4 mph. These speeds were identified during pilot testing as providing low, medium, and high levels of difficulty among community-dwelling adults aged 70 and older.

At the start of each perturbation, the treadmill belt was stationary, and participants stood on the belt facing forward with their feet side by side. A slender, rectangular foam block (4 × 4 cm cross section) was positioned approximately 3–7 cm in front of the toes to elicit a step over an obstacle, similar to that needed after a trip. Participants were instructed to, on treadmill movement, take steps to clear the obstacle and prevent a fall into the harness, and establish a consistent gait. Participants were also instructed to take their first step over the block with a particular foot (see Supplementary Material for more details). Within 20 s after these instructions, and without warning, the treadmill belt was accelerated to the speed set by the operator (Figure 1). The direction and speed of the treadmill belt acceleration were unknown to participants prior to each trial. Perturbations at 1.6 or 2.4 mph were not attempted if the participant either (a) opted out, or (b) did not attempt a step, or required substantial harness and/or spotter support during both perturbations at the next lowest speed (suggesting low performance at the current speed, and therefore likely low performance at a higher speed). Participants wore a fall protection harness, supported by an overhead gantry, to prevent knee or hand contact with the treadmill in the event of an unsuccessful attempt to recover balance. The length of the harness was set so that support was provided when participants fell vertically 20–25 cm.

The RBR rating method used video recordings (at 100 Hz) that provided a sagittal plane view of the treadmill and participant. For each perturbation, the following rating method was used (Figure 2). First, the amount of support provided by the harness or a spotter standing next to the participant was rated as a 0, 1, or 2. Second, the quality of the stepping response was rated as a 0, 1, or 2. Third, a rubric was used with these ratings of support and stepping response to determine an overall perturbation rating of 0, 1, or 2. The overall perturbation ratings were then summed across the six perturbations involving posterior belt acceleration to determine each participant's RBR that ranged from 0 to 12. Time-lapse photographs of several trials, along with their support rating, stepping rating, and RBR, are included in Supplementary Material. To assess the reliability of RBR, a second investigator rated all individual perturbations.

Reactive Balance Kinematics

Multiple measures of reactive balance kinematics were also determined from each perturbation. Measures of stepping kinematics were derived from the video recordings. Trunk kinematics were derived from sagittal plane trunk angle sampled at 128 Hz using an inertial measurement unit (APDM, Inc., Portland, OR) worn inferior to the suprasternal notch with a shoulder strap. Measures of reactive balance kinematics included time from the onset of treadmill movement

Figure 1. Photograph of a participant performing a reactive balance test. Visible is the harness and overhead gantry that prevented falls in the event of an unsuccessful test, and spotters on either side of the resident.

Support rating
0 = substantial harness and/or spotter support (subject would likely have fallen without support)
1 = moderate harness and/or spotter support (unclear whether subject would have fallen without support)
2 = no/minimal harness and/or spotter support

Stepping response rating
0 = no step OR block remains in front of toe after first attempt to step over block
1 = short shuffle step(s) before stepping over block OR wrong foot steps over block OR steps on top of block with correct foot
2 = correct foot clears block during first step AND second step clears block

Balance recovery rating (BRR)
0 = when support = 0 OR stepping response = 0
2 = when support = 2 AND stepping response = 2
1 = for all other cases

Figure 2. Reactive balance rating was determined for each individual treadmill perturbation by (a) rating the extent of support the participant experienced, (b) rating the quality of the stepping response, and (c) combining these two subratings into the reactive balance rating.

to liftoff of initial recovery step (step LO time), time from the onset of treadmill movement to touchdown of initial step over the block (step TD time), length of initial step over the block (step length), and maximum sagittal plane trunk angle from vertical after the onset of treadmill movement (see Supplementary Material for further details). These measures are similar to those used in prior assessments of reactive balance after treadmill perturbations (5,10,11) and have been shown to differ between successful and failed recoveries after trip-like perturbations (11).

Clinical Tests of Balance and Mobility

Participants also completed six clinical tests of balance and mobility that predict fall risk including: timed-up-and-go test (21), unipedal stance time (22), maximum step length (23), Berg Balance Scale (24), Performance-Oriented Mobility Assessment (POMA) (25), and Activities-specific Balance Confidence Scale (ABC) (26) (see Supplementary Material for further details).

Analyses

Prior to statistical analyses, measures of reactive balance kinematics were converted to a five-level (0–4) ordinal scale. This was done to permit the inclusion of perturbations during which participants did not respond appropriately (ie, did not attempt to step) or perturbations that were not attempted (ie, due to opting out). A similar approach was used earlier in the development of the Short Physical Performance Battery (27). Four steps were involved in this conversion. First, each participant's mean step LO time, step TD time, and step length over the two perturbations at each speed were determined. If a participant's stepping response rating (Figure 2) was a 0 for a given perturbation, or if a participant did not attempt a given perturbation, then that trial was not used when calculating the mean step TD time and step length. Second, the mean maximum trunk angle over the two perturbations at each speed was determined. If a participant's support rating (Figure 2) was a 0 for a given perturbation, or if a participant did not attempt a given perturbation, then that perturbation was not used when calculating the mean (because the support received may have substantially influenced maximum trunk angle). Third, if both perturbations at a given speed were excluded from the mean for the above-noted reasons, then the measure was assigned a value of 0 on the ordinal scale. Fourth, quartiles were calculated for the mean values at each speed. Participants in the lowest (poorest performing) quartile were assigned a value of 1 on the ordinal scale, participants in the second lowest quartile were assigned a value of 2, and so on. In our statistical analysis of reactive balance kinematics, we only used 0.8 and 1.6 mph trials due to the large percentage of 2.4 mph perturbations assigned a 0 on the ordinal scale (43% of participants for measures related to stepping kinematics, and 89% of measures of mean maximum trunk angle).

Agreement between the two raters of the ratings of individual perturbations was evaluated using the kappa statistic, and inter-rater reliability of the overall RBR (after summing across the six perturbations) was evaluated using the intraclass correlation coefficient (ICC(2,1)). Correlations between RBR, reactive balance kinematics (ordinal scale), and clinical tests were determined using Spearman rank correlation coefficients. To determine whether correlations between RBR and clinical tests were stronger than correlations between reactive balance kinematics and the same clinical tests, we used the method of Myers and Sirois (28) to compare Spearman correlation coefficients. In addition, differences in RBR between high-risk and low-risk participants were investigated using a Wilcoxon Rank Sum test. Established cutoffs for each clinical test were used to separate participants into two groups, and separate groupings were formed for each clinical test. The cutoffs predicted participants to be at a high risk for falling if timed-up-and-go test was greater than 13.5 seconds (29), unipedal stance time was less than 5 seconds (22), maximum step length was shorter than the median (no established cutoff), Berg Balance Scale was less than 45 (24), POMA was 24 or lower (25), and ABC was less than 67% (30). Statistical analyses were performed with JMP (SAS, Cary, NC) and a significance level of .05.

Results

RBR had a median of 4 (minimum = 0, maximum = 11) and increased as performance on clinical tests improved (see Supplementary Material for additional descriptive statistics on RBR and reactive balance kinematics). RBR was reliable across raters, with a kappa statistic of 0.86 for the ratings of individual perturbations, and an ICC(2,1) of .96 for the overall RBR after summing across all six perturbations.

RBR was correlated with all four measures of reactive balance kinematics. Spearman correlations were .19–.55 across all measures and both speeds, including .55 and .49 for step length (at 0.8 and 1.6 mph, respectively), .40 and .38 for step LO time, .45 and .34 for step TD time, and .19 and .45 for maximum trunk angle. All of these correlations were significant ($p < .046$) except for a correlation of .19 between RBR and maximum trunk angle at 0.8 mph ($p = .265$).

RBR exhibited a stronger correlation with clinical tests than reactive balance kinematics exhibited with clinical tests (Table 2). RBR had higher Spearman correlations with clinical tests than (a) step length (at either 0.8 or 1.6 mph) for five of six clinical tests; (b) step LO time for three of six clinical tests; (c) step TD time for one of six clinical tests; and (d) maximum trunk angle for all six clinical tests. RBR was 42%–60% lower among participants at a high risk for falling when using each of the six clinical tests to classify fall risk ($p \le .05$; Figure 3).

Discussion

Our goal was to develop and validate a low-tech RBR method in the context of trip-like treadmill perturbations. To evaluate the validity of RBR with respect to reactive balance performance, we hypothesized that RBR would be correlated with reactive balance kinematics. This hypothesis was supported, suggesting RBR to be a valid surrogate measure of reactive balance kinematics. RBR has the advantage that it only requires a video recording, whereas the other reactive balance kinematic measures investigated here and elsewhere require additional equipment and/or technical resources. RBR also benefits from incorporating multiple aspects of the dynamic reactive response that existing evidence supports as being important in preventing a fall after tripping (discussed more on the following page). Thus, RBR is more likely to be responsive to these treadmill-based intervention studies.

To evaluate the validity of RBR with respect to fall risk, we posed two hypotheses. We hypothesized that the correlations between RBR and clinical tests that predict fall risk would be stronger than the correlations between reactive balance kinematics and the same clinical tests. We also hypothesized that RBR would be lower among participants predicted to be at high risk for falls compared with those predicted to be at low risk. Both of these hypotheses were supported,

Table 2. Spearman Rank Correlation Coefficients Between RBR and Clinical Tests and Between Kinematic Measures and Clinical Tests

		TUG (s)	UST (s)	MSL (in)	Berg	POMA	ABC (%)
RBR		−.45	.51	.47	.44	.44	.43
Step length (ordinal)	0.8 mph	−.12*	.06**	.18*	.08*	−.08*	.21
	1.6 mph	−.01**	.28	.07**	.06**	.12*	.24
Step LO time (ordinal)	0.8 mph	−.34	.15**	.09**	.19	.28	.12*
	1.6 mph	−.32	.42	.14*	.32	.47	.29
Step TD time (ordinal)	0.8 mph	−.35	.17*	.25	.18	.21	.24
	1.6 mph	−.48	.34	.36	.37	.46	.24
Max trunk angle (ordinal)	0.8 mph	−.01**	.05**	−.07**	−.02**	.14*	.11*
	1.6 mph	−.22	.23*	−.01**	.11*	.30	.16

Note: ABC = Activities-specific Balance Confidence Scale; Berg = Berg Balance Scale; LO = liftoff; MSL = Maximum step length; POMA = Performance-Oriented Mobility Assessment; RBR = reactive balance rating; TD = touchdown; TUG = Timed Up and Go; UST = Unipedal Stance Time.

*Spearman correlation is smaller than RBR correlation with same clinical test ($p < .1$). **Spearman correlation is smaller than RBR correlation with same clinical test ($p < .05$).

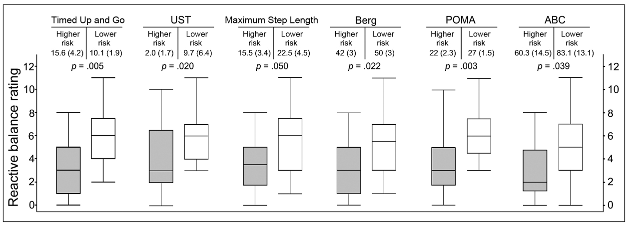

Figure 3. Box and whisker plots of reactive balance rating for fall risk groups identified using each of the six clinical tests. Boxes show median, 75th percentile, and 25th percentile for each group. Whiskers show the range for each group.

suggesting RBR to be a valid indicator of fall risk. RBR exhibited only minimally stronger correlation with the clinical tests than step TD time. However, as noted in the preceding paragraph, RBR has the advantages that it is easier to calculate than step TD time, and accounts for any support from the harness or spotters, whereas step TD time does not. RBR was also highly reliable across two raters. Taken together, these results support the potential clinical value of the RBR method as a reliable and valid low-tech measure of reactive balance performance after trip-like perturbations on a modified treadmill that require many steps to recover.

This study had limitations that warrant mention. First, the test–retest reliability of RBR has yet to be evaluated and may be compromised by the short-term adaptation in reactive responses to postural perturbations seen in prior studies (11). Second, although our results indicate RBR is correlated with clinical tests that are fall risk relevant, the ability of RBR to identify fallers and/or predict future falls is unknown and should be the participant of future studies. We are also not aware of any studies using reactive balance assessments after trip-like treadmill perturbations to predict falls outside the lab prospectively. Third, maximum trunk angle measurements may have been influenced by harness support in some participants/perturbations. Unlike harness support systems in many research laboratories that allow the anchor point to translate in the anterior–posterior direction as a participant steps (essentially limiting support to only the vertical direction), the anchor point of the harness on the gantry was fixed and did not allow this translation. This was a result of using a smaller, more portable fall prevention system that was installed onsite in senior congregate housing facilities. As a result, some harness support was generated if the participant moved too far forward or backward from the gantry during testing, even if there was no downward movement of the torso.

Prior studies using modified treadmills to train reactive balance after trip-like perturbations have used motion capture systems to measure stepping and trunk kinematics (5,10,11). In particular, these measurements included trunk angle and angular velocity (5,10,11), pelvis height (5), step length (5,11), anterior–posterior distance between the body center of mass and the stepping foot (5,11), and time from treadmill movement onset to lift off of initial recovery step (11). We investigated similar kinematic measures, yet these measures were less strongly correlated with estimated fall risk than RBR. There are at least two potential explanations for these findings. First, reactive balance after a trip-like postural perturbation has multiple requisites to avert a fall, including arresting trunk motion, maintaining adequate hip height to allow continued stepping, and expanding the base of support by stepping so the ground reaction force can contribute to decelerating the forward fall (31,32). Accomplishing all three of these requisites is necessary to successfully avert a fall, and kinematic measures that focus on only one of these aspects do not provide a sufficiently comprehensive view of reactive balance. RBR is a more "global" measure that includes multiple aspects of reactive balance. Second, it could be argued that the potentially less accurate video-based method we used to obtain kinematic measures of stepping negatively influenced the correlation with clinical tests. We cannot discount this possibility, but feel any such loss of accuracy is a consequence of training outside of the research setting with limited options for quantitatively assessing reactive balance with minimal resources and technical expertise.

RBR evaluates the reactive stepping response to an externally imposed postural perturbation, which is a distinct balance and fall-related skill that differs from static and nonreactive balance that is the general focus of clinical tests. In fact, studies have shown that reactive balance responses are not necessarily associated with static balance (33,34). We are aware of three studies of reactive balance training involving stepping among older adults that included as outcome measures some of the same clinical tests as in the present study. These studies reported no differential training effects between reactive balance training and control interventions on the timed-up-and-go test (7), Berg Balance Scale (7), ABC (7), unipedal stance time (35), and POMA (36), whereas other measures of falls or stepping did show improvements after training. These results align with the specificity of training principle (14), in that the greater similarity of reactive balance training with RBR than clinical tests suggests RBR is more likely to be responsive to these types of interventions than these clinical tests. Because it assesses critical aspects of reactive balance for avoiding a fall after tripping, the RBR, in contrast to clinical tests, may also help with understanding the specific biomechanical mechanism(s) for deficits in reactive balance (eg, stepping or trunk control) and can inform subsequent training to target these deficits.

In conclusion, an RBR method was developed and shown to correlate with reactive balance kinematics and clinical tests predictive of fall risk. Due to minimal resource and training requirements, RBR may provide a practical and valid measure to assess reactive balance performance and fall risk during reactive balance training in a clinical setting.

Supplementary Material

Supplementary data is available at *The Journals of Gerontology, Series A: Biological Sciences and Medical Sciences* online.

Funding

This work was supported by the National Institutes of Health (R21 AG045723 to M.L.M., P30 AG024824 to N.B.A.); National Science Foundation (HRD-1502335); Office of Research and Development of the Department of Veterans Affairs; and the Michigan Institute for Clinical and Health Research (UL1TR000433).

Acknowledgments

We thank Achu Byju and Debra Strasburg for their contributions to this project, and the staff at the following senior communities in Bryan/College Station, TX: Watercrest at Bryan, Crestview, Carriage Inn, Waldenbrooke Estates, Terrace Pines, Villas of Rock Prairie, and The Waterford at College Station.

Conflict of Interest

N.B.A. is an Associate Editor for *Journals of Gerontology: Medical Sciences*.

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