

# Postural Stability and Gait among Older Adults with Age-Related Maculopathy

Joanne M. Wood,<sup>1,2</sup> Philippe F. Lacherez,<sup>1,2</sup> Alex A. Black,<sup>1,2</sup> Michael H. Cole,<sup>2,3</sup> Mei Ying Boon,<sup>1,2</sup> and Graham K. Kerr<sup>2,3</sup>

**PURPOSE.** To assess the postural stability and gait characteristics of adults with age-related maculopathy (ARM) and to identify the visual factors associated with postural stability and gait in this clinical population.

**METHODS.** Participants included 80 individuals with a range of severity of ARM (mean age, 77.2 years). Binocular visual function measures included visual acuity, contrast sensitivity, and merged binocular visual fields. Postural stability was assessed on both a firm and a foam surface using center-of-pressure measures derived from a force platform. Forty three of the participants underwent a three-dimensional motion analysis to quantify gait characteristics, including walking velocity, proportion of time spent with both feet in contact with the ground (double-support time), stride length, and step width.

**RESULTS.** After adjustment for age, sex, self-reported physical function, and cataract severity, all the vision measures were significantly associated with postural stability on the foam surface, with contrast sensitivity being the strongest correlate. In the analysis of the gait measures, only contrast sensitivity was significantly associated with walking velocity, step width, or stride length, whereas contrast sensitivity and visual field loss were both significantly associated with double-support time.

**CONCLUSIONS.** Impaired contrast sensitivity was associated with postural instability, slower walking velocity, increased step width, and reduced stride length. Impairments in either contrast sensitivity or visual fields were associated with increased double-support time. This result suggests that loss of contrast sensitivity and visual fields in patients with ARM can lead to balance and mobility problems. (*Invest Ophthalmol Vis Sci.* 2009;50:482-487) DOI:10.1167/iovs.08-1942

Effectively navigating through a complex environment requires successful integration of both sensory and motor functions. Loss of visual function may pose significant challenges to an individual in terms of such integration. Among those with low vision, important visual cues for effective locomotion may be degraded. As a result, individuals may require more time or effort to navigate safely through the environment. Although the mobility problems of individuals with age-related

macular degeneration (ARM) have been well documented,<sup>1-5</sup> much less is known about the mechanisms underlying these problems. In the present study we assessed the balance and gait characteristics of individuals with ARM and sought to identify the visual factors associated with these characteristics in this population.

Older adults with ARM demonstrate greater magnitudes of sway than do age-matched control subjects when postural stability is measured under conditions of reduced somatosensory feedback.<sup>1,6</sup> This suggests that individuals with ARM are more likely to fall during times of somatosensory disruption (such as walking on carpeted flooring),<sup>1</sup> given that decreased postural stability is associated with an increased propensity for falling.<sup>7,8</sup> Reduced contrast sensitivity has been shown to be the strongest visual predictor of increased postural sway in independent, community-dwelling older adults,<sup>9</sup> and in a smaller sample of adults with ARM.<sup>1</sup>

The walking and mobility characteristics of adults with ARM have largely been measured during navigation through specially designed "mobility courses," where performance is usually expressed as time to complete the course and/or ability to avoid obstacles. On these courses, the performance of adults with ARM has been found to be worse than that of age-matched control participants in low,<sup>10</sup> but not in high levels of illumination.<sup>4,10,11</sup> In studies in which investigators have considered the range of performance within subjects with ARM, variations in mobility performance were associated with reductions in visual fields and contrast sensitivity,<sup>4,5</sup> or the level of ARM (as defined by fundus appearance).<sup>12</sup> To date, the specific gait characteristics of individuals with ARM have been measured in only two studies, and the results have demonstrated that adults with ARM walk more slowly and cautiously (shorter stride length and longer time for stride and stance) than do age-matched controls.<sup>2,3</sup> These differences were more apparent when walking on different surface types, although they were not related to the ambient level of illumination.<sup>2,3</sup> However, the specific aspects of visual function that were associated with these gait adaptations were not examined.

Collectively, the results of these studies have shown that individuals with ARM have problems with various aspects of mobility and balance compared to those with normal vision. We sought to extend these findings by identifying which measures of visual function are associated with these balance and gait difficulties. The postural stability and gait characteristics of older adults with ARM were assessed by using the gold standard measures of postural stability<sup>13</sup> and three-dimensional motion analysis,<sup>14</sup> and standardized, validated measures of visual acuity, contrast sensitivity, and visual fields were included as visual function measures.

## METHODS

### Participants

Eighty community-dwelling individuals with retinal changes consistent with a diagnosis of ARM were recruited to participate in the study. Participants were either recruited from the School of Optometry Clinic

From the <sup>1</sup>School of Optometry, the <sup>2</sup>Institute of Health and Biomedical Innovation, and the <sup>3</sup>School of Human Movement Studies, Queensland University of Technology, Brisbane, Australia.

Supported by the NHMRC (National Health and Medical Research Council) Prevention of Injuries in Older People Partnership in Injury grant.

Submitted for publication February 27, 2008; revised June 12 and August 5, 2008; accepted October 27, 2008.

Disclosure: **J.M. Wood**, None; **P.F. Lacherez**, None; **A.A. Black**, None; **M.H. Cole**, None; **M.Y. Boon**, None; **G.K. Kerr**, None

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked "advertisement" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Corresponding author: Joanne M. Wood, School of Optometry, QUT, Kelvin Grove, Brisbane Q 4059, Australia; j.wood@qut.edu.au.

at Queensland University of Technology, via the electoral roll, or from Brisbane-based members of the Macular Degeneration Foundation (Sydney, Australia).

Participants were required to have no significant ocular or visual pathway disease leading to visual field loss, other than ARM. They were excluded from the study if they were unable to walk unaided, had a history of Parkinson's disease, diabetes, or peripheral neuropathy, or showed signs of dementia (Mini Mental State Examination score  $<24$  of a possible 30).<sup>15</sup> The research complied with the tenets of the Declaration of Helsinki, and informed consent was obtained before the assessment. The research was approved by the Queensland University of Technology Human Research Ethics Committee.

### Vision Assessment

All participants underwent an eye examination, including assessment of the presence and severity of lens opacification, with the slit lamp-based Lens Opacities Classification System (LOCS III).<sup>16</sup> For the purpose of analysis, the highest LOCS score (nuclear, posterior subcapsular, or cortical) in the eye with the better visual acuity was used as the level of cataract severity. The severity of ARM was graded independently from fundus slide photographs of each participant, according to the AREDS classification scheme.<sup>17</sup> The average of the AREDS grades for the two eyes was used in the analysis, as it places greater weight on participants with equal degeneration in both eyes, representing more severe impairment.

Binocular high-contrast visual acuity with each participant's habitual distance refractive correction was measured with a Bailey-Lovie high-contrast letter chart at a working distance of 3.2 m and an average luminance of 195 cd/m<sup>2</sup>. Participants were instructed to guess letters, even when they were unsure, until a full line of letters was incorrectly read. Visual acuity was scored as the total number of letters read correctly, converted to logMAR units. Contrast sensitivity was measured binocularly with the paper version of the Melbourne Edge Test,<sup>18</sup> at a working distance of 40 cm and an average luminance of 65.5 cd/m<sup>2</sup>, with an appropriate near correction. Participants were asked to identify the orientation of the edge within each circular patch until two consecutive incorrect responses were made, and the lowest contrast edge correctly identified recorded as the participant's contrast sensitivity in decibels. Visual fields were assessed with a computerized perimeter (Humphrey Field Analyzer; model HFA-II 750; Carl Zeiss Meditec Inc., Dublin, CA). Monocular 24-2 SITA-standard threshold tests were performed by an experienced optometrist. A binocular mean deviation (MD) score was derived by merging the right and left fields to create a binocular visual field, based on the more sensitive of the two eyes at each visual field location.<sup>19</sup>

### Postural Sway Assessment

Postural sway was assessed by using standardized techniques that have been used in previous studies of balance,<sup>1,6,20</sup> on two different surfaces (firm and foam), with eyes open and with participants wearing their habitual walking spectacle correction. For the firm surface condition, participants were positioned in the center of a force platform (AccuSway; Advanced Mechanical Technology Inc., Watertown, MA) and asked to stand as still as possible for a period of 30 seconds. For the foam surface trials, the participants stood on a medium-density, 15-cm thick block of foam with a surface area of 50 cm<sup>2</sup>, which was positioned over the surface of the force platform. This condition reduced the somatosensory input to balance control. For both conditions, the participants were instructed to place their feet 10 cm apart while gazing directly ahead at a cross subtending 1.43° in width that was mounted on a wall. To ensure the participants' safety, a member of the research team stood nearby to help steady the participants if they became unbalanced. During each 30-second trial, center-of-pressure data were collected by the force platform at a sampling rate of 50 Hz and provided information on the anterior-posterior and mediolateral sway of the individual. The extent of postural sway was represented by the overall length of the center-of-pressure path for the firm and the

foam surface. Several common measures derived from the center-of-pressure data were compared (anterior-posterior and mediolateral extent, RMS amplitude, elliptical area, and rectangular area). Of these measures, path length had the best predictive validity, in that this measure had more robust correlations with the vision measures at the bivariate level, and these bivariate relationships better met the assumptions of multiple regression in having evenly distributed, or homoscedastic residuals. Path length has also been shown to be a strong predictor of postural instability and falls in previous prospective studies.<sup>21</sup> Because of equipment problems, data from only 77 participants were available for analysis.

### Gait Assessment

Forty-three participants (those who were recruited via the Optometry Clinic or Macular Degeneration Foundation) also completed a gait assessment while wearing their habitual walking spectacle corrections. Each participant was asked to walk at a self-selected and comfortable pace along a firm walkway measuring 12 m (six trials) at an average illumination of 468 lx. To remove any influence of shoe design on gait characteristics, the participants performed the trials barefooted, which is in accordance with methods used in previous clinical gait assessments.<sup>22,23</sup> Twenty-eight spherical markers were positioned on the body in accordance with the Helen Hayes marker set,<sup>24</sup> which was modified to include the upper body. Markers were attached to the trunk (sacrum, sternum, and C7 spinous process), arms (lateral border of the acromion, olecranon process of the humerus, and radial and ulnar styloids), and head (supra-auricular point and the top of the head). During the walking trials, the motion of these markers was tracked at a rate of 50 Hz with a six-camera, three-dimensional motion-analysis system (Peak Motus 2000; Vicon, Oxford, UK). The three-dimensional position of the markers was used to calculate stride length, double-support time (percentage of time spent with both feet in contact with the ground), step width (distance between right and left heels during double support), and walking velocity (stride length divided by stride period)<sup>25</sup> as shown in Figure 1. The selection of these variables was based on the knowledge that older individuals often seek to reduce stride length and walking velocity and increase double-support time in an attempt to minimize postural instability.<sup>26</sup>

### Questionnaire

A measure of physical function was derived from the SF-36 physical function scale. This self-reported measure was used to provide an index of the general physical functioning and health of the participants and has been shown to be an effective and valid healthcare measure in older community-based populations.<sup>27</sup>

### Statistical Analyses

We examined the association of the vision measures with the postural sway and gait outcome measures. Characteristics considered likely to be associated with visual impairment, postural sway, and gait characteristics were included as potential confounders (age, sex, physical function, and cataract severity). To assess the relative contributions of each vision variable to each of the postural sway and gait outcome measures, while maximizing the ratio of cases to variables, we performed a series of stepwise regression analyses with a forward-selection procedure. The forward-selection technique is appropriate in instances where the goal is to derive a minimal set of predictor variables that maximize prediction of a given criterion.<sup>28</sup> First, partial correlations were examined for each independent variable/dependent variable pair controlling for the covariate set. Then, multivariate regressions were performed in which entry to the model was controlled by whether the inclusion of the variable in the model significantly improved model performance.

### RESULTS

Demographic characteristics, visual function, postural stability, and gait data for the participants are given in Table 1, and the

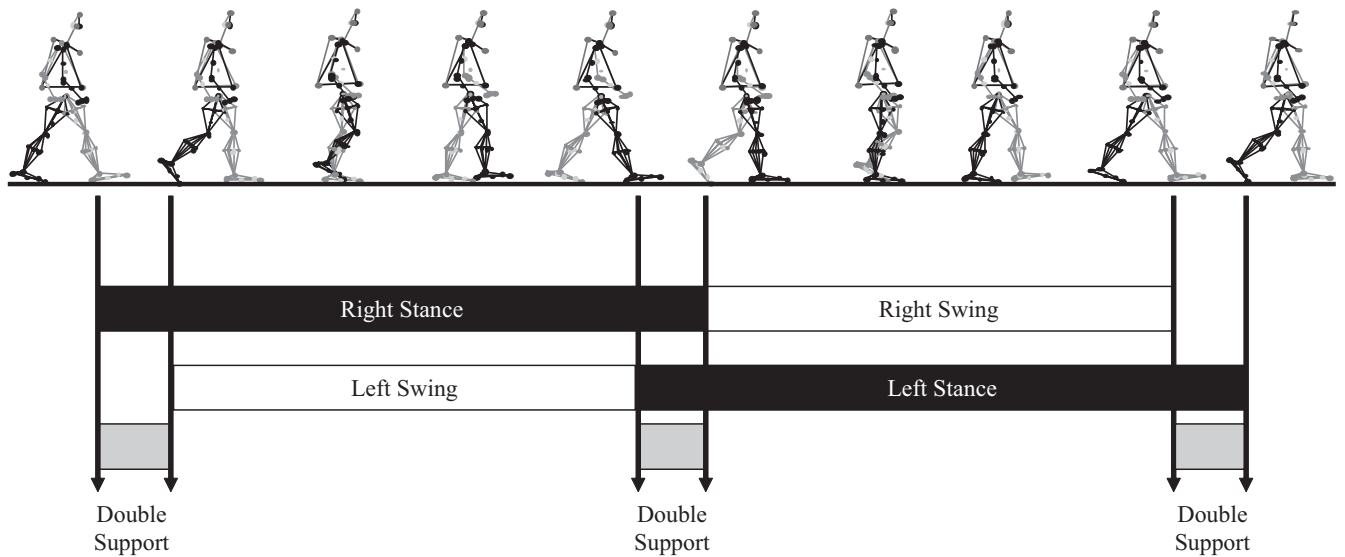


FIGURE 1. The events measured in the gait cycle. Double support is defined as the time during which both feet are in contact with the ground. The black leg is the left one.

range of AREDS classifications of participants in the sample is presented in Table 2.

The mean age of the participants was 77.2 years with a range from 59 to 95 years of age. There were more women than men in the sample (36 men, 44 women), which is typical of those with ARM.<sup>29</sup> There was a wide range of severity of ARM within our participants, according to their AREDS score and the level of their binocular visual acuity, contrast sensitivity, and visual field loss. The subset of participants who took part in the gait assessments ( $n = 43$ ) were younger on average (mean age = 75.8 years, SD = 7.2) and overall had poorer visual function (mean visual acuity = 0.39 logMAR, SD = 0.47) than those who did not. All participants undertook the balance and gait assessments wearing their habitual walking spectacle correction which included 32% wearing bifocals, 23% progressive lenses, 4% trifocals, 5% single correction, and 36% no correction. No differences were found for any of the sway or gait outcome measures according to the type of habitual walking spectacle correction worn.

The postural stability and gait characteristics of our sample of individuals with ARM also demonstrated a wide range of performance levels across the group. The effect of disrupting the information from the somatosensory system by standing on foam was highly significant, where the length of the center-of-pressure path on the foam surface was longer than that on the firm ( $t(76) = -14.05, P < 0.001$ ).

TABLE 1. Group Mean, Standard Deviation and Range for Vision, Postural Sway, and Gait Measures

	Mean (SD)	Range
Age (y)	77.18 (6.89)	59-95
Binocular visual acuity (logMAR)	0.31 (0.42)	-0.14-1.38
Binocular contrast sensitivity (dB)	16.43 (4.57)	5-24
Binocular field mean deviation (dB)	-2.8 (4.44)	-21.89-3.46
AREDS score (average of both eyes)	2.37 (1.12)	1-4
Postural sway on firm (cm)	36.92 (12.06)	18.17-87.39
Postural sway on foam (cm)	52.04 (22.99)	24.94-155.3
Walking velocity (m/s)	1.08 (0.25)	0.66-1.73
Double support (%)	24.85 (4.83)	15.53-38.83
Step width (m)	0.18 (0.06)	0.07-0.3
Stride length (m)	1.14 (0.19)	0.73-1.5

Table 3 shows the partial correlations between the vision measures and the performance measures of postural sway and gait including walking velocity, stride length, step width, and double-support time. Covariates were age, sex, physical function, and cataract severity. Table 4 shows the multivariate linear regression models for each outcome measure.

Contrast sensitivity, visual acuity, and visual field loss were all significantly associated with postural stability on the foam surface at the bivariate level. Figure 2A shows the relationship between contrast sensitivity and postural sway on foam. For each measure, reductions in visual function were associated with greater postural instability, after controlling for the covariate set. In the multivariate model (Table 4) the only vision measure that was significant was contrast sensitivity, indicating that the other vision variables did not significantly add to the prediction of postural sway on the foam surface after contrast sensitivity was taken into account. None of the vision variables were correlated with sway on the firm surface.

At the bivariate level, contrast sensitivity was significantly associated with all four of the gait measures after adjustment for the covariate set, whereas visual field loss was only significantly associated with double-support time, and the AREDS score was associated with walking velocity and stride length. Poorer scores in these vision measures were associated with shorter stride length and wider step width, slower walking velocity, and longer double-support time (illustrated for contrast sensitivity and walking velocity in Fig. 2B). Visual acuity was not significantly associated with any of the gait measures. In the multivariate model only contrast sensitivity was significantly associated with these gait characteristics. The other

TABLE 2. AREDS Classification of the Participants

AREDS Score	Participants, $n$ (%)	
	Better Eye	Worse Eye
0-1 (early)	22 (27.5)	12 (15)
2 (early to mid stage)	21 (26.3)	14 (17.5)
3 (mid stage to advanced)	14 (17.5)	16 (20)
4 (advanced)	18 (6.3)	33 (41.3)
Missing	5 (6.3)	5 (6.3)
Total	80 (100)	80 (100)

TABLE 3. Partial Correlations between Vision Measures (Independent Variables) and Sway and Gait Variables (Dependent Variables)

	Sway on Firm	Sway on Foam	Walking Velocity	Stride Length	Step Width	Double-Support Time
Binocular contrast sensitivity	-0.04	-0.33*	0.40†	0.35†	-0.36†	-0.34†
Binocular visual acuity	0.08	0.29†	-0.19	-0.12	0.28	0.13
Binocular visual field	-0.01	-0.28†	0.24	0.20	-0.31	-0.32†
AREDS score	0.00	0.13	-0.32†	-0.33†	0.28	0.27

Data are adjusted for age, sex, physical function, and cataract severity.

\*  $P < 0.01$ .

†  $P < 0.05$ .

vision measures did not significantly add to the prediction of these outcome measures after reductions in contrast sensitivity were taken into account (Table 4).

For those bivariate analyses where visual field loss was significantly associated with the sway and gait outcome measures, we also explored the question of whether visual field loss in the upper or lower hemifield was more strongly associated with these outcome measures, again controlling for the same covariates. Greater inferior field loss was found to be the better predictor of increased sway (inferior,  $r = -0.324$ ; superior,  $r = -0.212$ ), while greater superior field loss was the better predictor of increased double-support time (inferior,  $r = -0.186$ ; superior,  $r = -0.414$ ).

## DISCUSSION

Our study demonstrated that increasing visual impairment due to ARM was significantly associated with postural instability and gait problems measured within a controlled laboratory environment. Poorer visual function was associated with greater postural instability and gait adaptations including shorter steps, wider stance, slower walking speed, and more time spent with both feet on the ground. Of the visual functions examined, contrast sensitivity was the strongest individual predictor of each outcome, whereas visual fields were related to only some of the gait parameters. It is likely that these associations will be even stronger in the real-world environment, which is far more visually challenging, and in a frailer population.

We found that contrast sensitivity was the only visual function measure significantly associated with sway on a foam

surface, when the visual function measures were combined in a multivariate model. This is consistent with the findings of Elliott et al.,<sup>1</sup> who reported a significant association between contrast sensitivity and postural sway in the foam condition in adults with ARM, but little association between postural sway and central visual field measures. Our findings are also in accord with balance studies from general older populations, where reduced contrast sensitivity was the strongest independent visual predictor of postural sway.<sup>9</sup> The finding that visual function was predictive of postural stability on the foam and not the firm surface was not unexpected, given that the contribution of vision to postural stability increases under conditions of reduced somatosensory input.<sup>9</sup>

Furthermore, we found that contrast sensitivity was the only visual function measure significantly associated with the gait adaptations in the multivariate models. The gait adaptations associated with reduced contrast sensitivity included shorter strides, wider steps, slower walking speed, and more time spent with both feet on the ground. These characteristics have been postulated to be representative of a more conservative walking pattern and are thought to occur due to an increased degree of caution being adopted by a particular individual.<sup>26,30,31</sup> Although our study is the first to investigate the visual predictors of gait adaptations in ARM, Spaulding et al.<sup>2</sup> demonstrated that those with ARM, compared with control subjects, also adopt more cautious gait patterns when walking in challenging environments.

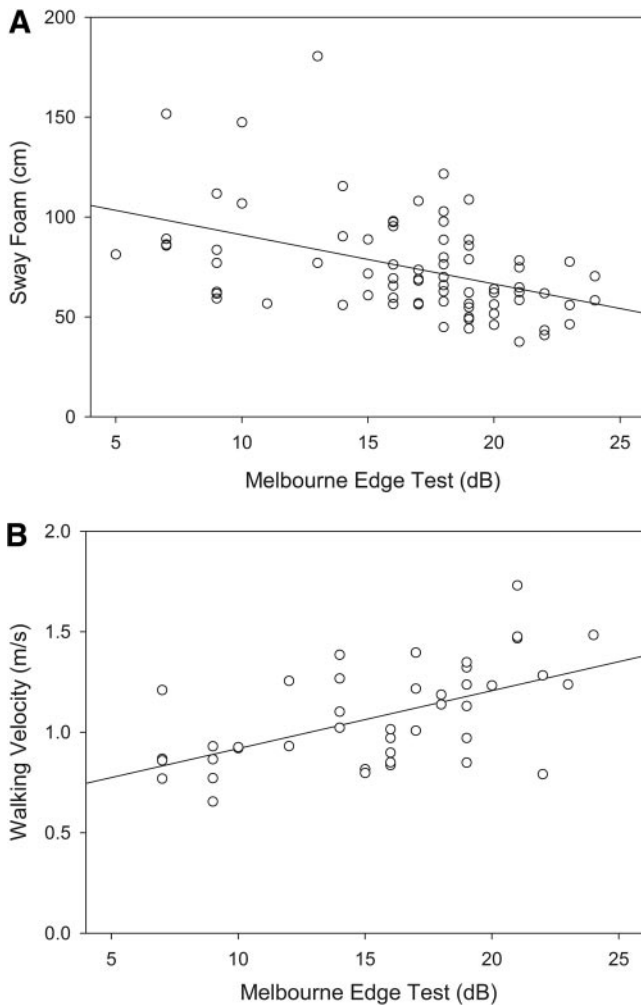
The finding that contrast sensitivity is the best predictor of gait adaptations complements previous mobility research involving relatively complex obstacle courses.<sup>4,5</sup> These studies suggest that the most important predictors of mobility perfor-

TABLE 4. Stepwise Multiple Regression Analyses

	Sway on Foam		Walking Velocity		Stride Length		Step Width		Double-Support Time	
	Beta	P	Beta	P	Beta	P	Beta	P	Beta	P
Variables included										
Age	0.44	<0.01	-0.39	0.01	-0.30	0.04			-0.32	0.03
CS	-0.27	0.01	0.37	0.01	0.35	0.02	-0.45	<0.01	0.39	0.01
Sex					-0.28	0.03				
Variables not included										
Age							0.22	0.16		
Sex	0.08	0.42	-0.05	0.71			-0.15	0.30	0.13	0.29
PF	0.19	0.05	0.19	0.14	0.17	0.21	0.04	0.77	-0.25	0.06
Cataract	-0.15	0.13	-0.03	0.82	0.02	0.89	-0.01	0.97	0.03	0.85
Fields	-0.04	0.77	0.00	0.82	-0.02	0.92	-0.15	0.44	-0.19	0.30
VA	0.13	0.44	0.30	0.19	0.32	0.16	-0.12	0.65	-0.31	0.19
AREDS score	-0.20	0.17	0.10	0.65	-0.05	0.84	-0.03	0.90	-0.12	0.63

Vision measures were used as predictors. Age, sex, physical function, and cataract severity were the covariates, and postural sway on a foam surface, walking velocity, stride length, step width, and double-support time were the dependent variables. Variables included in the final model are shown at the top of the table. Variables not included in the final model are presented together with their respective beta-to-enter values. CS, contrast sensitivity; PF, physical function; VA, visual acuity.





**FIGURE 2.** Relationship between contrast sensitivity (Melbourne Edge Test) and path length for sway on a foam surface (A) and walking velocity (B).

mance in patients with ARM were impaired contrast sensitivity and visual fields. It is likely that the contribution of visual field loss in safe navigation through these complex mobility courses is greater than that found in this study due to the inclusion of peripheral obstacles and increased path complexity. Of note, the findings in the present study indicate that visual field loss was significantly associated with increased double-support time in the bivariate analyses, suggesting that a combination of visual field and contrast sensitivity may play an important role in determining the gait adaptations among older adults with ARM. Previous research has suggested that falls may occur more frequently in those individuals with inferior field loss.<sup>32</sup> However, while our findings suggest that greater inferior field loss was more strongly associated with increased postural sway, greater superior field loss was more strongly associated with increased double-support time.

This study has important strengths in that we have used well-established and standardized measures of postural stability, gait, and visual function. Our measure of postural stability based on force platform data and the three-dimensional motion analysis are considered to be gold-standard measures of balance<sup>13</sup> and gait.<sup>14</sup> There are, however, several limitations that should be addressed in further research. First, although the sample size used in these analyses is larger than many others in this field, the large degrees of freedom for the effects (the

number of predictors and covariates in the model) reduce the power of some analyses. Further research using larger samples would strengthen the conclusions made. It would also be useful to investigate the relationship between changing visual function and gait longitudinally within an ARM sample, rather than cross-sectionally. Further research is also needed to examine whether these changes found in our laboratory-based study are also mirrored during real-world navigation in both novel and familiar environments.

In summary, this study demonstrated that visual impairment among older adults with various levels of ARM affects postural stability and gait characteristics. Impaired contrast sensitivity was associated with postural instability, slower walking velocity, increased step width, and reduced stride length, whereas impairments in either contrast sensitivity or visual field sensitivity were associated with increased double-support time. These findings suggest that eye care providers should be aware that increasing loss of contrast sensitivity and visual fields in their patients with ARM may lead to difficulties in balance and mobility.

### Acknowledgments

The authors thank The Macular Degeneration Foundation (Sydney, Australia) for assistance in recruiting participants; all the participants who gave so generously of their time; and Roger Martin, Melissa Newton, Matthew Roodveldt, Jocelyn Stewart, Oren Tirosh, and Paul Turner for assistance in various stages of the laboratory-based data collection.

### References

1. Elliott DB, Patla AE, Flanagan JG, et al. The Waterloo Vision and Mobility Study: postural control strategies in subjects with ARM. *Ophthalmic Physiol Opt.* 1995;15:553-559.
2. Spaulding SJ, Patla AE, Elliott DB, Flanagan J, Rietdyk S, Brown KS. Waterloo Vision and Mobility Study: gait adaptations to altered surfaces in individuals with age-related maculopathy. *Optom Vis Sci.* 1994;71:770-777.
3. Spaulding SJ, Patla AE, Flanagan J, Elliott DB, Rietdyk S, Brown KS. Waterloo Vision and Mobility Study: normal gait characteristics during dark and light adaptation in individuals with age-related maculopathy. *Gait Posture.* 1995;3:227-235.
4. Hassan SE, Lovie-Kitchin JE, Woods RL. Vision and mobility performance of subjects with age-related macular degeneration. *Optom Vis Sci.* 2002;79:697-707.
5. Kuyk T, Elliott JL. Visual factors and mobility in persons with age-related macular degeneration. *J Rehabil Res Dev.* 1999;36:303-312.
6. Turano KA, Dagnelie G, Herdman SJ. Visual stabilization of posture in persons with central visual field loss. *Invest Ophthalmol Vis Sci.* 1996;37:1483-1491.
7. Tinetti ME, Speechley M, Ginter SF. Risk factors for falls among elderly persons living in the community. *N Engl J Med.* 1988;319:1701-1707.
8. Turano KA, Rubin G, Herdman S, Chee E, Fried L. Visual stabilization of posture in the elderly: fallers vs. nonfallers. *Optom Vis Sci.* 1994;71:761-769.
9. Lord SR, Menz, HB. Visual contributions to postural stability in older adults. *Gerontology.* 2000;46:306-310.
10. Brown B, Brabyn L, Welch L, Haegerstrom-Portnoy G, Colenbrander A. Contribution of vision variables on mobility in age-related maculopathy patients. *Am J Optom Physiol Opt.* 1986;63:733-739.
11. Wilcox DT, Burdett R. Contrast sensitivity function and mobility in elderly patients with macular degeneration. *J Am Optom Assoc.* 1989;60:504-507.
12. Klein R, Klein BEK, Knudtson MD. Frailty and age-related macular degeneration: The Beaver Dam Eye Study. *Am J Ophthalmol.* 2005;140:129-131.

13. Vuillerme N, Chenu O, Pinsault N, Boisgontier M, Demongeot J, Payan Y. Inter-individual variability in sensory weighting of a plantar pressure-based, tongue-placed tactile biofeedback for controlling posture. *Neurosci Lett*. 2007;421:173-177.
14. McLean SG, Walker K, Ford KR, Myer GD, Hewett TE, van den Bogert AJ. Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. *Br J Sports Med*. 2005;39:355-362.
15. Heun R, Papassotiropoulos A, Jennssen F. The validity of psychometric instruments for detection of dementia in the elderly general population. *Int J Geriatr Psychiatry*. 1998;13:368-380.
16. Chylack LT Jr, Wolfe JK, Singer DM, et al. The Lens Opacities Classification System III. The Longitudinal Study of Cataract Study Group. *Arch Ophthalmol*. 1993;111:831-836.
17. The Age-Related Eye Disease Research Group. The Age-Related Eye Disease Study (AREDS) system for classifying age-related macular degeneration from stereoscopic color fundus photographs: AREDS Report No. 6. *Am J Ophthalmol*. 2001;132:668-681.
18. Verbaken JH, Johnston AW. Population norms for edge contrast sensitivity. *Am J Optom Physiol Opt*. 1986;63:724-732.
19. Nelson-Quigg JM, Cello K, Johnson CA. Predicting binocular visual field sensitivity from monocular visual field results. *Invest Ophthalmol Vis Sci*. 2000;41:2212-2221.
20. Lord SR, Menz HB, Tiedemann A. A physiological profile approach to falls risk assessment and prevention. *Phys Ther*. 2003;83:237-252.
21. Lord SR, Clark RD, Webster IW. Postural stability and associated physiological factors in a population of aged persons. *J Gerontol*. 1991;46:M69-M76.
22. Lord SR, Lloyd DG, Li SK. Sensori-motor function, gait patterns and falls in community-dwelling women. *Age Ageing*. 1996;25:292-299.
23. Chan GNY, Smith AW, Kirtley C, Tsang WWN. Changes in knee moments with contralateral versus ipsilateral cane usage in females with knee osteoarthritis. *Clin Biomech*. 2005;20:396-404.
24. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. *J Orthop Res*. 1990;8:383-392.
25. Perry J. *Gait Analysis: Normal and Pathological Function*. Thorofare, NJ: Slack Incorporated; 1992.
26. Woollacott MH, Tang PF. Balance control during walking in the older adult: Research and its implication. *Phys Ther*. 1997;77:646-660.
27. Chia EM, Rochtchina E, Wang JJ, Mitchell P. Utility and validity of the self-administered SF-36: findings from an older population. *Ann Acad Med Singapore*. 2006;35:461-467.
28. Tabachnick BG, Fidell LS. *Using Multivariate Statistics*. 5th ed. Boston: Allyn and Bacon; 2007.
29. van Newkirk MR, Nanjan MB, Wang JJ, Mitchell P, Taylor HR, McCarty CA. The prevalence of age-related maculopathy: the visual impairment project. *Ophthalmology*. 2000;107:1593-1600.
30. Maki BE. Gait changes in older adults: predictors of falls or indicators of fear? *J Am Geriatr Soc*. 1997;45:313-320.
31. Sudarsky L. Geriatrics: Gait disorders in the elderly. *N Engl J Med*. 1990;32:1441-1446.
32. Coleman AL, Cummings SR, Yu F, et al. Binocular visual-field loss increases the risk of future falls in older white women. *J Am Geriatr Soc*. 2007;55:357-364.