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Exploring the feasibility and acceptability of sensor monitoring of gait and falls in the homes of persons with multiple sclerosis

Pamela Newland[a,*], Joanne M. Wagner[b], Amber Salter[c], Florian P. Thomas[d], Marjorie Skubic[e], Marilyn Rantz[f]

[a] Goldfarb School of Nursing at Barnes Jewish College, 4483 Duncan Avenue, Mailstop 90-36-697, St. Louis, MO 63110F, United States
[b] Department of Physical Therapy and Athletic Training, Doisy College of Health Sciences, St. Louis University, St. Louis, MO 63104, United States
[c] Division of Biostatistics, Washington University School of Medicine, St. Louis, MO 63110, United States
[d] Neuroscience Institute at Hackensack University Medical Center (HUMC), New Jersey, United States
[e] Electrical and Computer Engineering, University of Missouri, Columbia, MO 65211, United States
[f] Curators' Professor Emerita Sinclair School of Nursing, University of Missouri, Columbia, MO 65211, United States

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ABSTRACT

Gait parameters variability and falls are problems for persons with MS and have not been adequately captured in the home. Our goal was to explore the feasibility and acceptability of monitoring of gait and falls in the homes of persons with MS over a period of 30 days. To test the feasibility of measuring gait and falls for 30 days in the home of persons with MS, spatiotemporal gait parameters stride length, stride time, and gait speed were compared. A 3D infrared depth imaging system has been developed to objectively measure gait and falls in the home environment. Participants also completed a 16-foot GaitRite electronic pathway walk to validate spatiotemporal parameters of gait (gait speed (cm/s), stride length (cm), and gait cycle time(s)) during the timed 25 foot walking test (T25FWT). We also documented barriers to feasibility of installing the in-home sensors for these participants. The results of the study suggest that the Kinect sensor may be used as an alternative device to measure gait for persons with MS, depending on the desired accuracy level. Ultimately, using in-home sensors to analyze gait parameters in real time is feasible and could lead to better analysis of gait in persons with MS.

1. Introduction

Multiple sclerosis (MS) is a progressive illness that affects the central nervous system (CNS) often resulting in various degrees of disability (National MS Society [NMSS]) [1]. Even though [long term loss of independence and increased disability are main concerns voiced by persons with MS, a majority still live in their own homes] [2]. Gait and balance problems affect approximately 75% of people with MS [3], they contribute to falls, adversely affect quality of life (QOL), and may lead to injury [4]. With approximately 80% of cases diagnosed as relapsing–remitting MS at onset, relapses play an important role in determining subsequent prognosis and the development of disability level [5]. [One recent longitudinal study [6] representing persons with MS, found gait velocity was significantly associated with increasing disability and progression. In addition, slower gait velocity is reported to be predictive of falls, cognitive problems, and injuries in persons with MS] [7–9]. In patients' perception, gait is considered the most valuable function [10,11]. Reduced gait speed or reduced variable step length are associated with increasing disability and falling in persons with MS [8].

[While gait parameters have been quantified in the laboratory setting, they have not been studied in the home environment. Studies [12–14] have examined gait parameters, such as speed variability of velocity, using body-worn sensors in people with MS and healthy controls. One important thing these studies lack is the immediate feedback provided by in-home mounted sensors. While body-worn sensors can detect mobility differences, detection of commonly described abnormal temporal-spatial gait parameters (e.g., velocity, step length, base of support) are warranted to strengthen the inconsistencies in prior studies. Thus, it seems that the evidence as to the association between gait and falls in persons with MS, is limited.]

* Corresponding author.
E-mail addresses: Pamela.Newland@bjc.org (P. Newland), jwagne34@slu.edu (J.M. Wagner), amber@wubios.wustl.edu (A. Salter), thomasfp@slu.edu (F.P. Thomas), SkubicM@missouri.edu (M. Skubic), rantzm@missouri.edu (M. Rantz).

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To date, no studies have used real time depth sensors to identify gait problems and falls in people with MS in their home environment. Most previous research assesses walking in a short duration clinic setting (e.g., <6 min) [15,16]. While accelerometer data provide abundant information regarding physical activity [7], this technology does not provide detailed real-time information on specific gait parameters and falls. Due to lack of recall and changes in location of where persons with MS walk and fall, prior measures may not adequately reflect real time gait and fall assessment. Thus it is important to assess persons with MS in the home. We postulate that gait monitoring in the home environment will contribute to the longitudinal assessment of worsening gait problems and falls in persons with MS.

A 3D infrared depth imaging system (SensorForesite Healthcare System) has been developed to measure gait and falls in the home environment objectively. This system has been validated in the geriatric population [17] (Fig. 1). The details of the system are described elsewhere [13,18]. Briefly, 3D infrared depth cameras are used to sense a room environment. The floor plane is detected, and people are segmented as they move through the environment, effectively creating 3D silhouettes while maintaining the privacy of the person being monitored. A tracking algorithm is used to identify walks [14]. The system calculates stride length, stride time, and walking speed by analyzing the motion of these 3D silhouettes. As part of a larger study, our goal here was to explore the feasibility and acceptability of monitoring of gait and falls in the homes of persons with MS over a period of 30 days.

2. Methods

2.1. Participants

This study represents subjects from a larger study. Participants were recruited from a MS clinic in the Midwest and a database of previous research participants. The inclusion criteria were: [internet access, age 18 years or above, diagnosis of any subtype of MS, no relapse in the prior 30 days due to possible increase in Self-Report Expanded Disability Status Scale (SR-EDSS) score [19],]

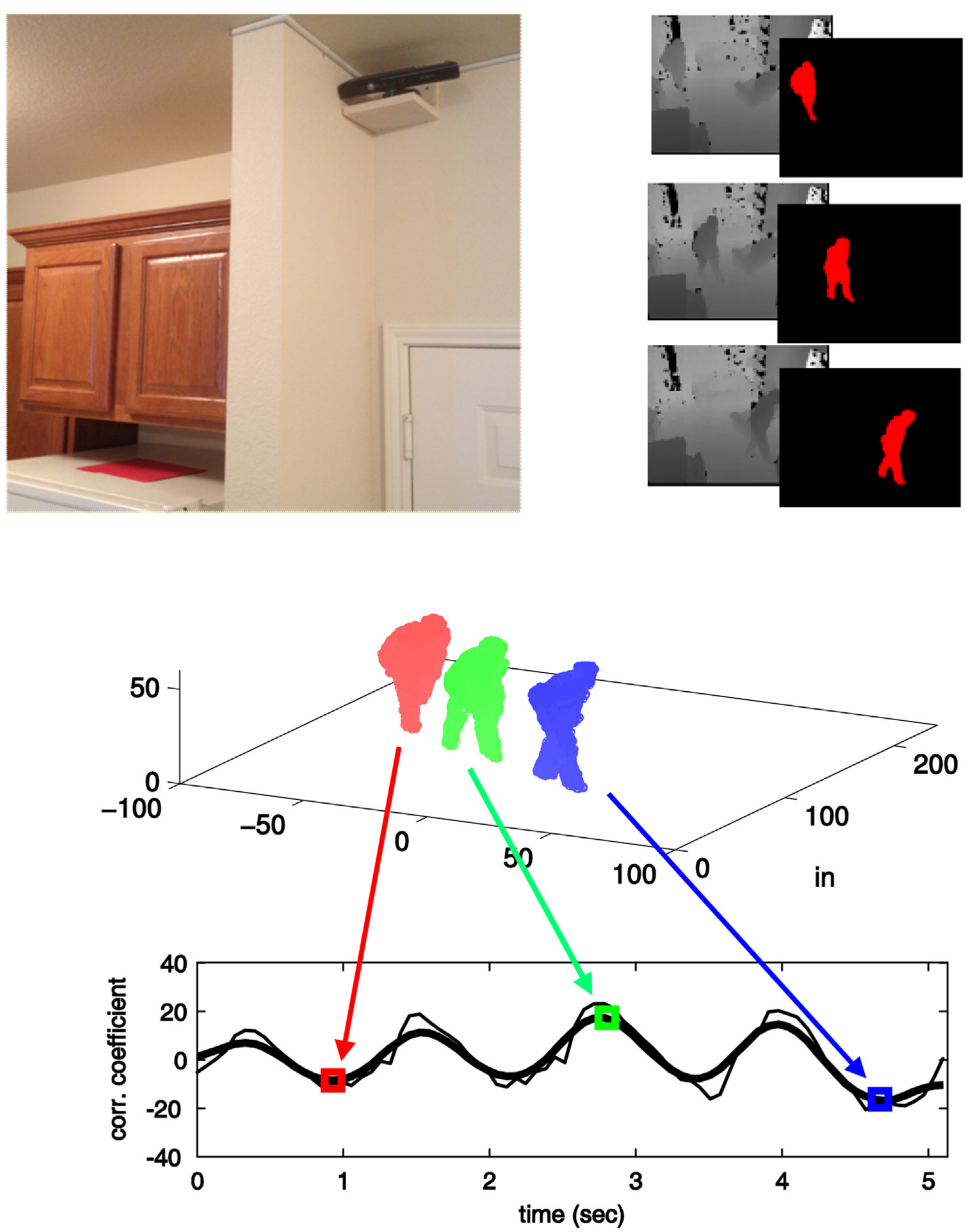

Fig. 1. Sensor placement (a) and sensor silhouette. Wang.

SR-EDSS score of 0 to 6.5, and self-reported ≥2 falls in the last 6 months. Persons with MS unable to give consent were excluded. Informed written consent was obtained from eligible participants. The research study was approved by Institutional Review Board at Saint Louis University and Goldfarb School of Nursing

2.2. Demographic and Clinical Measures

At baseline, demographic and other self-report characteristics were collected (age, education, race, gender, BMI, medications). *The SR-EDSS* was used to measure disability status. The scale reflects the functional system components and is highly correlated with the ($r = 0.92$) physician version EDSS scores. The scale divides functioning into eight functional systems: pyramidal, cerebellar, brainstem, cerebral, bowel and bladder, sensory, visual, and other; impairment in each system are graded and then summed across the eight systems. The SR-EDSS has a possible score range of 0 (normal neurological exam) to 10 (death due to multiple sclerosis).

2.3. Clinical Gait Measures

In the gait laboratory setting, participants completed a 16-foot GaitRite electronic pathway walk (GAITRite Gold, CIR Systems, PA, USA) which was used to validate spatiotemporal parameters of gait (gait speed (cm/s), stride length (cm), and gait cycle time (s) during the T25FWT) [8]. The GAITRite system is an electronic walkway that is connected to a personal computer via an interface cable. The walkway comprises a series of sensor pads that are inserted in grid formation between a layer of vinyl (top cover) and foam rubber (bottom cover). Data from the activated sensors is collected by a series of on-board processors and transferred to the computer through a serial port. In addition, to assess feasibility and acceptability of collecting fall risk with the sensor system, each participant completed a monthly fatigue/pain/fall log (developed by Newland).

2.4. In-home Monitoring of Gait

In-home gait systems using the depth sensors were installed in the main living area of each home, as shown in Fig. 2 (an exemplar of one subject's apartment). To preserve the privacy of the research subject, only the depth images (an image where the value of each pixel depends on its distance from the camera) that appear as shadow-like silhouettes from the gait system are captured [13]. Walking segments of four feet or greater occurring in view of the systems are automatically identified, segmented, and analyzed for gait speed, height of the individual walking, stride time, and stride length. Using these data, a model representing each participant's gait was created, and then updated over time using data from the prior 30 days. The average in-home gait speed (AIGS) of a person with MS for a given day was computed as a weighted average of gait speed from all segmented walks in the home during the prior seven days. The depth sensor image was processed to compute gait parameters of stride time, stride length, velocity, and falls. These gait parameters were validated in previous work against the Vicon marker-based motion capture system in the laboratory and showed good agreement [20]. The number of walks detected by the sensor that can be used to compute the measurement depends on a variety of factors, including layout of the home, clutter, system positioning, and subject behavior. Fall algorithms were modified so that all falls and non-fall events were correctly identified in the Kinect depth image data [21]. We also asked for self-report of time in the home during waking hours to match with the depth sensors.

Fig. 2. Placement of sensor in one participant's apartment.

2.5. Procedure

Eligible participants came to the research laboratory for baseline clinical gait assessments and to complete other study measures. At this point, participants completed written informed consent. The participants were instructed that the depth sensors would be placed in their homes to capture gait for first 30 days. Foresite staff (the sensor company that provided the sensors for this study) then contacted them for placement of the sensors within two weeks of the baseline assessment. The sensor captured and transmitted data over broadband internet servers to a secure database. Approximately four weeks after baseline, participants were called for the short acceptability interview.

2.6. Data Analysis

Data were analyzed using SPSS 22 and SAS 9.4 (SAS Institute, Cary NC). While the sensors collected information for 6 months, we only considered the first 30 days of the study period in order to define feasibility. Additionally, a priori the association between the clinical and sensor gait information was evaluated only at the time point closest to the baseline visit and then again 30 days later. Means (standard deviations), medians (interquartile range) and frequencies were used to describe continuous and categorical variables as appropriate. The relationship between measures was assessed using Spearman's correlation. Falls recorded by self-report on the fall logs were noted in frequencies. We used content analysis [18] to code participants' responses and develop themes from the interviews, which was used to confirm acceptability (e.g., qualitative reports of how the depth sensors worked to capture their gait and falls).

3. Results

3.1. Feasibility, Acceptability, and Attrition

For this study, 21 persons with MS were contacted about participating, with a final sample of seven. However, multiple reasons explain lack of recruitment of participants. Six persons with MS failed screening due to not meeting fall eligibility criteria, and one subject did not qualify due to having a relapse (Table 1). Seven persons with MS did not want to participate because they felt the sensors would invade their privacy, and one had transportation issues to come to the laboratory for baseline visit. We also documented barriers to feasibility of installing the in-home sensors (Table 1) (e.g., installation problems, internet connectivity issues, and placement of camera to capture falls

Table 1
Barriers and summary of screen failures.

Issue	Explanation	Result/response
Sensor installation	Some sensors had technical issues; wireless connectivity problems in some participant housing	Insufficient data collection
Sensor placement	In the study consent, participants were informed that the sensor would be mounted on the wall. However, some participants refused sensor mounting and opted to have sensor placed on a tripod	Sensors that were not mounted on the wall reported less data than those that were mounted
Insufficient recruitment	Privacy concerns limited some recruitment	Failure to recruit 20 pwMS

and straight path walking). Despite problems with recruitment, seven participants were enrolled in the study with average number of days reported in Table 3.

3.2. Participant Characteristics

The seven participants who had sensors installed in their homes were on average 52 years old (range = 41-67). Most (n = 5) had an education level of some college, were women (n = 5), single (n = 4), and White (Table 2). The sample was comprised mainly of the relapsing remitting subtype, with median SR-EDSS score of 5, indicating moderate disabilities (Table 2).

3.3. In Home Sensor Gait Measures Feasibility

For the first 30 days of the study, the sensors captured gait information every day for 4 participants with the other 3 subjects ranging from 5 to 27 days of recording (Table 3). The gaps for participants were a result of technical issues with the internet (Participant 4) and a hospitalization (Participant 6). A major concern was internet connectivity and placement of the sensors. One participant had an interruption due to pay as you go internet services. Participants with a stronger broadband internet connection did not report any concerns about connectivity. The smaller gaps in participants one, two, and five were corroborated with their reported days outside of the home (hospitalized, living elsewhere). For the days the sensor captured data, the average number of walks recorded was a median of 8 and an interquartile range (25%, 75%) of (3.4, 9.7) per day. Gait parameters reported here were feasible in measurement of stride length, stride time, and gait speed (as found in Rantz et al. [21]).

Secondly, fall logs were used to compare sensor data with the subject's self-report of falls. The frequency of falls (n = 2-3) self-reported for two participants were not detected by the sensor. This is likely due to the small sample size (n = 7 participants) and falls occurring outside view of sensor (e.g., outdoors) (Table 1).

Table 2
Participant Demographic and Clinical Characteristics.

Characteristic	
Sex, n (% n)	
Female	4 (57.1)
Male	3 (42.9)
Race, n (% n)	
White	5 (71.4)
African American	2 (28.6)
Marital Status, n (% n)	
Married	4 (57.1)
Single	2 (28.6)
Divorced/Separated	1 (14.3)
Age (years), mean (SD)	50.7 (9.2)
BMI, mean (SD)	28.7 (6.8)
Education (years), mean (SD)	13.7 (2.1)
Years since diagnosis, mean (SD)	12.2 (8.2)
Self-report EDSS, median (IQR)	5 (4.5, 6.0)
AFO use, (% n)	
No	5 (71.4)
Yes	2 (28.6)
Number of self-report falls in past 6 months, median (IQR)	2 (2, 5)
Number of near falls in past 6 months, median (IQR)	6 (2, 20)
Disease Modifying Therapy, (% n)	
Injectable	3 (42.9)
Infusion	1 (14.3)
Oral	3 (42.9)
Medication Use, (% n)	
Ampyra	1 (14.3)
Amantadine	1 (14.3)
Vitamin D	6 (85.7)

Note: interquartile range (IQR).

3.4. Acceptability of the In Home Sensor Gait Measures

A subset of participants (n = 4) participated in one time, semi-structured interviews [18] conducted approximately four weeks after initiating the depth sensors in the home. The transcribed interviews with persons with MS resulted in interesting comments [20]. The participants elaborated on their likes and dislikes about the sensors. For example, participants were asked "*if the sensors made them more aware of gait and/or falls.*" One participated reported, "*felt it made them more aware of their gait.*" Other responses included: "*it was non-intrusive.*" We asked if having the sensor made them more aware of walking in the home? One comment: "I *think it makes me more careful when I'm in front of the sensor because actually the falls I've had, so on the fall risk thing. . So I notice that I'm more careful in front of the sensor, really I am.*" Another said: "*Would you recommend this system . . . if it's going to help somebody, if it's going to help everybody I think it's something that people should do.*" One less favorable comments was: *"Installation took a long time . . . put on, like a ledge, you know, but it wasn't catching my walking so that's when they, came back and put it on a tripod."*

A few of the participants felt the sensor could be useful for detecting problems with their gait. Two participants felt that the intervention could have been provided for shorter period. Likewise, most stated they were in the home at least 16 of 24 h each day during the 30 day period that data were being collected.

4. Discussion

In this paper, the feasibility and acceptability of the in home sensor for gait and fall assessment in community-living people with MS was examined. To our knowledge, our study is the first study which has used the Kinect depth sensor to assess gait and falls in the homes of people with MS.

The present findings show that an in home depth sensor with more detailed analysis of gait parameters is feasible. The algorithms were able to correctly identify and extract time- and speed-related measures from the sensor signals of all successfully completed walks for persons with MS. Findings from our research

Table 3
Average Number of Walks using In Home Gait Sensor in People with Multiple Sclerosis.

	N	Average number of walks per day, Mean (SD)	Gaps in Recording over the 30 days
1	27	9.7 (3.4)	3
2	30	12.5 (3.0)	0
3	30	9.0 (2.5)	0
4	5	2.0 (0.3)	5, 20
5	30	8.1 (2.8)	0
6	18	3.4 (0.6)	12
7	30	4.7 (1.1)	0

study indicate that using depth sensors in the home offers not only a feasible solution but is a cost-efficient and unobtrusive way to gather real-time gait parameters. However, detecting falls was not successful in this study in homes of persons with MS.

[This study (Tables 1 and 3), as well as work by others [18,20,24] found similar feasibility among measurement of gait parameters such as gait speed, walks per day, and stride length. Research has shown that gait speed, stride, and step length changes can contribute to disease progression [6,11]. Likewise, measuring day-to-day continuous gait parameter may identify early changes, as well as falls, and other adverse health outcomes in persons with MS [8–10].] Although we were able to obtain sensor data on gait parameters, falls were not so easily detected. [Our results for the measurement of falls are inconsistent with others who used the sensors in apartments of older adults [18,22,25], in which falls were detected and correlated with fall risk assessment tools.] In our study, the Kinect sensor was located in one living space, so it was possible for the persons with MS to fall outside of the view of the sensor camera. The location chosen for the Kinect sensor was planned to be sure gait parameters were collected several times each day. It was anticipated that falls were likely to occur in the high traffic areas selected for the gait detection. Interruptions in internet services were a study limitation. One subject had a plan based on usage which hindered data collection as data transmission increased his costs. Another had intermittent service, so sensor data was continually interrupted. Providing internet service in future studies would help the study to have complete data collection.

Another improvement would be to mount more than one sensor in the various living spaces to detect falls. In our study, as in others using sensors in older adults [13], only one fall sensor was deployed in each participant's home. Unlike the original research that captured many falls in the main living area of apartments, no falls were detected as the people with MS in this study fell outside the view of the sensor. One explanation is that, in the MS population, many still reside at home in 1–2 bedroom or larger homes and would need multiple sensors for monitoring purposes. [It is well documented that self-report of a fall is poorly recalled with increasing time between the actual fall event and the questionnaire in the study [8,9]. To increase feasibility findings specific to persons with MS, future studies might consider measuring step and activity count with in home sensors and another passive device such as a Fitbit [23].]

Completion of paper fall logs was varied, with missing data [averaging about 33%.] Since participants found paper logs cumbersome, in our future work we will evaluate shorter, possibly electronic methods, for the logs [24]. Possible other explanations of the missing data could be lack of recall, time, or just simply losing the paper work. [To compensate for the missing fall log data, our research team contacted those participants who did not mail back completed logs. During the follow up phone call, the team member would complete the missing data.] Phone calls may have introduced bias into the log data. A combination of research using the Kinect technology in a younger population like persons with MS [20] is needed as to find the best method for logging falls.

Despite a short intervention period (30 days), the sensors were able to monitor gait parameters in the home, albeit with some barriers to overcome for future studies. As technology continues to advance, the implementation of the sensors as a way to monitor and better study in home parameters of gait should only become easier. As we saw, what is observed in clinic is different from what is seen in the home. The ability to address that discrepancy with these systems, look for changes in gait in people with MS, and use sensor monitoring in future clinical trials and effectiveness evaluations could potentially fill an important gap in fall detection and fall risk assessment.

This study has the strength of the positive feedback from the participants as to the utility of these home sensors for future studies. As with any study, there are limitations to be mentioned. First, the sample was much smaller than we anticipated, thus limiting the generalizability of the sample to the general MS population. The sensor was limited due to sensor placement. Space in the home for an adequate walking path was often very limited, thereby limiting the space for fall detection and gait assessment. For example, some participants were unwilling to have wall installation of the sensor, so it was installed on a tripod. One participant was willing to have the sensor mounted on the wall for better viewing (Fig. 2), and walks were consistently detected in the recommended wall mounting installation. In prior work, the sensors worked well in confined spaces [13,17] using wall mount methods; therefore, it is difficult to compare results. Future studies might be strengthened by using continuous depth sensors in combination with body-worn devices.

For concerns with lack of recruitment, improved methods of marketing and education for the persons with MS about privacy-protecting images and actual method of the depth sensor could be beneficial. Although we did provide an explanation with a picture of the silhouette images from the Kinect to each participant before they were recruited, an actual demonstration or video of a demonstration may have helped recruitment. No concerns were raised by participants or families, although one participant did frequently move the sensor during the study; that was problematic because the sensor needed to be recalibrated when moved and it was easy for participants or visitors to move the tripod installation.

While we used rigorous criteria for recruitment and participants reported > 2 falls in the last 6 months, none had falls within the view of the sensors that were captured. In addition, self-reported estimates of the time spent in different areas of the home to determine the right location for placement of the sensor were not collected. Accommodating multiple geographical locations for recruitment of participants for future studies could hasten the process of participant recruitment, and thereby the evaluation process. Another recruitment strategy could be to broaden the criteria for participant inclusion to more easily achieve the desired sample size, for example, possible subgrouping of persons with MS with and without falls as a control group.

5. Conclusion

The use of in home sensors for identifying gait parameters and falls is an important objective method to be used in care of persons with MS. Interventions to prevent gait decline in persons with MS is critically important to reduce morbidity, mortality, and improve QOL. Using the Kinect sensors in the homes of persons with MS offers promising information on gait data in a privacy-protecting, unobtrusive way that can capture the events. Through our ongoing pilot study, researchers are optimistic that, despite the limitations, adequate gait data per day can be achieved to better assess people with MS. Ultimately, using in home sensors to analyze gait parameters and falls, should they occur, in real time could lead to better analysis of falls and fall risk that can aid in developing future fall prevention strategies. The long term goal of our research is to determine if subjective symptoms interact to impact gait and accidental falls in order to develop focused rehabilitation strategies.

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Conflict of interest

None.

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