Chapter

Smart Tracking and Wearables: Techniques in Gait Analysis and Movement in Pathological Aging

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Abstract

In this chapter, we describe the aging process and, more specifically, the pathological aging, associated with neurodegenerative diseases and its relation with gait. Then, we explain the importance of using quantitative gait analysis techniques using wearables and other technologies to diagnose different conditions that can be complex to discriminate using only the physician naked-eye diagnosis. We analyze different approaches used for gait analysis using wearables and affordable devices like inertial units (IMU), accelerometers, and depth cameras like Microsoft Kinect or Intel's RealSense, which have been available at least in an academic context but will be available for daily use in the near future.

Keywords: aging, Parkinson's disease, gait analysis

1. Aging

Aging of the population is one of the greatest current challenges because this implies a social transformation that includes work, economic, social protection, home, and coverage in health services. According to the data of World Population Prospects, the 2017 revision, it has been considered that most of the population has a life expectancy equal to or greater than 60 years, which is growing faster than the younger groups, and has estimated that by 2050, this group would increase globally to 2.1 billion, as well as 3.1 billion in 2100 [1].

1.1 Characteristics of aging

In the context of aging, physiological problems affect the brain. It has been considered that cognitive impairment and gait changes are the most significant since they have a high impact on the quality of life, so there is currently evidence in favor of neuroprotective strategies such as diet and exercise, especially in neurological diseases [2]. In recent years, it has increased the empirical evidence that suggests that the aging process could be delayed and, therefore, increase life expectancy accompanied by improvements in healthy lifestyle habits [3]. Likewise, advances in technological development have allowed the implementation of easy-to-use and adaptable devices to identify subtle markers of early symptoms that could be useful for designing intervention or stimulation programs in such a way as to positively influence the healthy aging process.

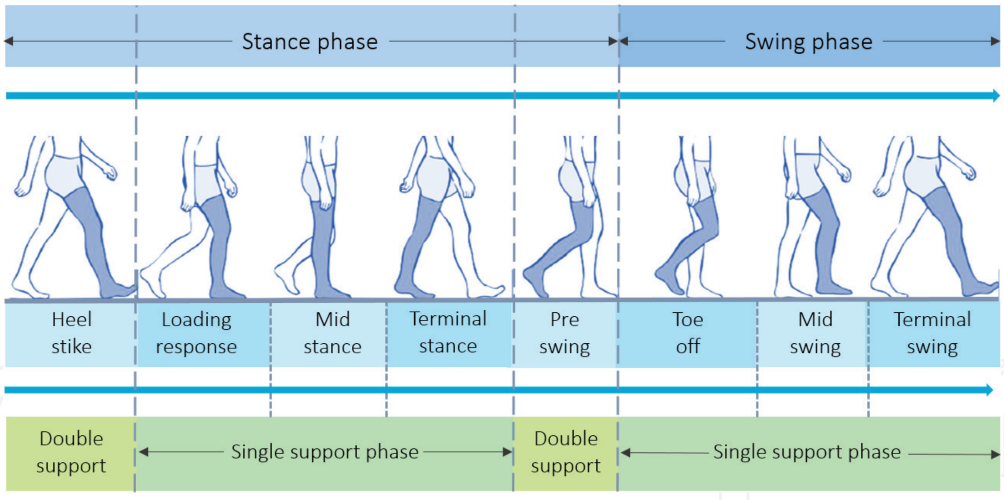

Figure 1.
Gait phases.

In advanced ages, a decline in sensorimotor functioning and control ensues. The causes of these deficits can be multifactorial and involve the central nervous system, sensory receptors, muscles, and peripheral nerves [4]. Falls are a frequent problem in the elderly population, and it has been determined that many of these occur in the context of walking. Older adults have less dynamic stability during walking due to the deterioration in the sensitivity of the body as well as the movement of the trunk in response to small disturbances that may occur during walking [5]. This deterioration in fine motor control, gait, and balance affects the ability of older adults to independently execute the activities of daily life which affects their autonomy and functionality. However, it is important to establish that gait and mobility are not the same thing. In gait, there is a bipedal activity in which the center of gravity moves forward and includes two components: (1) the locomotion as the ability to initiate and maintain the rhythmicity in the steps and (2) the balance that is the ability to maintain the balance and posture. On the other hand, mobility is the ability to displace in the environment with ease and without restriction. In adults, mobility is an important factor in the loss of functional independence. Walking is basic in human motion and can be studied by assessing the gait cycle. This cycle is described from the moment one foot strikes the ground until the same foot returns to the ground. The body displaces in space for specific distance and the cycle repeats. Components of the gait cycle include stride, distance covered from one-foot strike to striking the ground again; distance covered by each foot and it is symmetric in length for both sides. The frequency of stepping is called cadence, and it is described as the number of steps per minute (**Figure 1**).

1.2 Gait and aging

The neurophysiology of gait is a complex process that involves subcortical and cortical levels and executive aspects of attention and planning. Voluntary movements are always accompanied by postural control, which couples the programs that relate to the task with the adjustments of the movements and posture. The voluntary movement includes specific parts of the body, as well as adjustments of anticipation depending on the goal to be achieved. For the execution of the movements and the prediction of the postural programs, the cerebral cortex, the basal ganglia, the cerebellum, and the brainstem are used by descending systems that act on the spinal cord [6]. The signals from the basal ganglia and cerebellum control the excitability of the neurons in the cerebral cortex and brain stem by ascending and descending projections. All of these contributes to the planning, programming, and initiation of gait and, finally, modulates the rhythm and muscle tone during locomotion. It has been described that the loop formed by the basal ganglia, cerebellum, and the motor cortex can contribute to the purpose of the recalibration of the walking pattern to navigate in different environments [7]. The hierarchical organization of gait can also be described in several levels based on the classification of Hughlings Jackson [8]. The lower levels would be related to the cells of the anterior horns and the visual, vestibular, and proprioceptive system, which would be involved in the production of the force required for the balance and locomotion, as well as the sensory information, and would be associated with the orientation in the space in relation to the support surface. The middle level would modulate and refine the forces to stand, balance, and locomotion. Finally, the upper level would interpret and integrate the sensory input to select and organize the appropriate motor programs for the desired action [9].

The decrease in gait can predict a mild cognitive impairment suggesting that motor changes may appear earlier than cognitive deficits [10]. Variables such as speed would be considered the most sensitive measure in the older population and could be a common and final expression of the decline that may occur with aging even when there are no clinically significant alterations or subjective complaints in relation to gait and mobility.

Slowness in walking is associated with different factors, including risk factors such as high blood pressure (HBP), as well as changes in brain integrity age-related. Magnetic resonance (MR) studies in subjects without neurological disease have reported decreased volume in motor regions, the prefrontal cortex, the basal ganglia, and the medial temporal lobe. Among the structures described, the decrease in the right hippocampus, related to sensorimotor integration functions, as well as spatial memory, is strongly linked with cognitive deterioration profiles, as well as dementia. While speed could be considered useful in clinical screening, other studies indicate that it is also important to establish how gait parameters would be involved in aging since it has been reported that they could predict the risk of falls and loss in mobility affecting the quality of life [11]. The importance of these findings lies in the recognition of predictive factors that are easily accessible to clinicians who can detect early cognitive deterioration as well as dementia, which in turn will enable the creation of better strategies for planning, prevention, and treatment options [12].

As described above, the gait is multidimensional, and it is a challenge with age because it requires mechanisms of automaticity and cognitive control to maintain performance under different conditions and to mitigate the effects of age. A model of five domains has been proposed to understand the complexities of gait: step, rhythm, asymmetry, variability, and postural control to evaluate gait in older adults. Due to this, each character has different neural mechanisms involved. Within these domains, the pace, variability, and postural control were more sensitive when age was used as a criterion to discriminate the walking pattern. This could be related to cognitive control and the impact of executive commitment rather than the rhythm which is associated with circuits of the brainstem and the spinal cord [13]. In addition, speed has been the most used to evaluate, discriminate, and predict measurements throughout the life course since it has strong clinimetric properties [14].

Multiple factors contribute to maintaining the dynamics of gait; of these, the balance is considered a fundamental characteristic to achieve ambulation. Balance can be defined as the ability to control the body mass on a surface in order to maintain balance and orientation [15]. This process involves the integration of information from the nervous system, the sensory system, and the musculoskeletal system that allow the stabilization of the body mass during the activities of daily life [16]. The alteration of the balance in older adults is one of the most referred symptoms in the consultation, and when this is added to the gait alterations, they are considered predictors of falls [17]. It has been estimated that between 20 and 33% of adults over 65 experience balance problems; in addition to adults over 60, there is a 30% chance to fall at least in the first year, increasing by passing the 75 years [18].

2. Defining pathological aging: concepts from human locomotion

As previously described, gait depends on the integrity of the structures involved in both the planning—central nervous system—and the execution of motor tasks, peripheral nervous system and musculoskeletal system. While gait changes are common in older people, the presence of gait abnormalities suggests overt or covert pathologies [19]. Although some of these pathologies are easy to identify (e.g., sarcopenia), there are other conditions that represent a diagnostic challenge for the physician. This situation sometimes leads to the question: is this subject ill or just old? [20].

To answer this question, some authors differentiate the normal aging from the non-normal aging using the term "pathological" or "secondary aging." Secondary aging could be defined as an abnormal set of changes afflicting a segment rather than the entirety of the older population [21]. Trying to objectify the non-normal aging process and taking into account that many of these diseases affect the mobility and independence of the subjects, some authors have suggested that secondary aging could be assessed taking in to account the alterations in the gait pattern.

The frequency of gait disorders increase with age; some reports suggest that prevalence rises from 10% between 60 and 69 years to 60% in subjects over 80 years [22]. Some of these pathological motor changes include:

Reductions in gait speed: assessment of gait speed has been described as the sixth vital sign [23]; the preferred walking speed in older adults is a sensitive marker of general health and survival [24]. Although the decrease in speed could be considered normal during aging, some authors suggest that these reductions are associated with an incremented risk for developing mild cognitive impairment [25] and dementia [26–28]; also, gait slowness is related to bradykinesia considered one of the cardinal symptoms of Parkinson's disease (PD).

Reductions in stride length: reductions in stride length have been described in patients with PD [29, 30], subjects with small vessel disease [31], and osteoporotic women with recurrent falls [32].

Increased gait variability: gait variability measures are unaltered in healthy older adults. Studies suggest that an increased gait variability could be associated with an increase of fall risk and could be a marker of pathological conditions such as PD, stroke, Alzheimer, and Huntington disease [33].

Changes in arm swing: PD patients usually exhibit reduced arm swing magnitudes and a higher arm swing asymmetry even in early disease stages [33].

2.1 From muscle to brain: diseases that lead to gait disorders in the elderly

The abnormal conditions leading to pathological aging can be divided depending on the affected system; taking into account that some studies suggest that approximately two-thirds of those who had gait alterations also had neurological disorders, we present a three-level model adapted from the International Parkinson and Movement Disorder Society [19]:

Lower-level disorders: this level includes pathologies that affect muscle, neuromuscular joint, or bones like extreme sarcopenia and osteopenia.

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Middle-level disorders: this level includes brain white matter, basal ganglia, and cerebellum disorders. Parkinson's disease, Huntington disease, and cerebrovascular disease are included in this category.

High-level disorders: also called frontal-subcortical gait disorder.

2.2 Lower-level disorders

- Musculoskeletal gait disorders: osteoarthritis (inflammatory process involving bone) and lower limb skeletal deformities are the main non-neurological condition associated with non-normal gait changes in older adults [24]. Since most of these diseases affect articulations and mobility, they are usually assessed by measuring the range of motion (ROM) of the joint and its impact in gait speed. Some of the most common findings are summarized in **Table 1**.

Level	Anatomic localization	Pathology leading to secondary aging	Related motor changes
Lower level	Joints	Foot and ankle inflammatory arthritis	Decrease in walking speed, reduced cadence, increased double limb support, decreased step length, reduced sagittal plane ankle ROM [40]
		Knee osteoarthritis	Decrease in walking speed, larger knee adduction moment, smaller mid-stance knee flexion moment, larger knee flexion angles at heel strike [41]
		Hip osteoarthritis	Step length asymmetry [42, 43], reduced hip ROM
	Peripheral nerve	Diabetic neuropathy	Decrease in walking speed and cadence, shortening of stride length [44]
		Polyneuropathy	Decreased stride time, increased stance time, increased double support time, reduced hip ROM [45]
Middle level	Basal ganglia	Parkinson's disease	Decrease in walking speed, reduced step length, reduced arm swing magnitude, higher arm swing, and step asymmetry [33]
	Basal ganglia	Huntington disease (chorea)	Decrease in walking speed, shortening of step length, shortening of stride length [46], decreased swing time, and increased stance time
	White matter	Cerebrovascular and small vessel disease	Decrease in walking speed, shortening of stride length, decrease in cadence
	Cerebellar	Cerebellar disease	Decrease in walking speed and cadence [39]
High level	Frontal-subcortical gait disorder	Vascular, progressive supranuclear palsy (PSP), late Parkinson's disease, normal pressure hydrocephalus	Gait changes are not specific and are related to the pathology

Table 1.
Gait disorders summary.

- Peripheral nerve gait disorders: peripheral neuropathy is a general term describing disease affecting the peripheral nerves. Prevalence of neuropathic complications of some chronic disease as diabetes increases with aging [34]. Although other neuropathies are rare in elderly [35], some findings are reported in these age groups (see **Table 1**).

- Neuromuscular joint disorders: neuromuscular joint disorders as myasthenia gravis are more frequent in younger women; for that reason they are not discussed here.

2.3 Middle-level disorders

Parkinson's disease: PD is the second most common neurodegenerative disorder; its prevalence is dramatically increasing in older adults [36]. PD is characterized by a depletion of dopamine in the central nervous system leading to cardinal motor symptoms like bradykinesia (slowness of global motor tasks), tremor, postural instability, and rigidity. Objective changes in gait have been reported even in early PD stages and can be used to complement the diagnosis, follow up, and quantify the pharmacological response in these patients [33].

Senile or late adult-onset chorea: chorea refers to a group of movement disorders characterized by the "dancing" appearance of the affected body parts. Although its diagnosis is rare in elderly subjects, there is small a group of patients who debut with symptoms at late ages [37]. To our knowledge, there are no gait analysis studies in patients with late-onset chorea; some of the alterations found in other types of chorea are shown in **Table 1**.

Cerebrovascular disease: stroke is the second leading cause of death and a major cause of disability worldwide. Its incidence is increasing because of the population aging. Gait changes related to stroke depend on the location and extent of cerebral infarction. Given that hemiparesis is one of the most common motor features in the middle cerebral artery occlusion, most studies on gait analysis include hemiparetic patients [38]. See **Table 1**.

Cerebellar disease: cerebellar disease could be related to age-dependent (multiple sclerosis) or aging-dependent (cerebellum atrophy, chronic alcohol consumption, stroke involving cerebellum) pathologies [39]. In our knowledge there is no a single study that evaluates gait changes in cerebellar pathology due to aging. Some of the motor features due to cerebellar disease are summarized in **Table 1**.

2.4 High-level disorders

- Frontal-subcortical gait disorder: this syndrome includes disequilibrium unexplained by sensorimotor deficits, problems initiation or maintaining stepping (freezing of gait), and difficulty with foot placement. Gait changes are not specific.

3. From medical to engineering consultation: importance of the objective gait assessment

The clinical evaluation, within the medical consultation, of patients with movement disorders is usually subjective and has great intra- and inter-observer variability. This variability leads to difficulties in the diagnosis and the follow-up of patients. With the development of new technologies, the objective gait analysis has been more used in the research context. These technological devices allow to detect subtle motor changes even in early stages of the disease, usually when the physician cannot identify them using regular observation (naked eye). In the next sections, we will address the relevance of the objective gait analysis and the importance of precision medicine in the future of the diagnostic, follow-up, and decision-making processes of patients with neurologic and non-neurologic diseases.

4. Ecological assessment

Studies on the human body and phenomena that affect its functioning, such as diseases or aging, have an experimental design in which individuals are subjected to various tests for data collection.

Currently, clinical tests that consist of physical tests such as gait assessment are based on electronic measurement instruments, such as wearables, as seen in the previous section, which seeks to establish objective measures. However, to ensure the quality of the measurements, not only precision is required. Clinical tests may have the Hawthorne effect, which is not desirable.

This effect is that the people under study change their behavior because they are being observed. In the case of gait analysis, this implies that individuals alter their way of walking [47, 48]. In fact, Berthelot et al. [49] affirm that this effect should be taken into account during the clinical tests since they showed different results if they were tested blindly and found advantages in blind conditions for gait speed (GS) and timed up and go (TUG) tests.

The study by Robles-García et al. [50] has explored the impact of the effect on the gait analysis, evaluating 30 people, 15 with Parkinson's disease (PD) and 15 healthy people, 8 of whom were young and 7 elderlies. Gait variables such as cadence and gait speed were measured. The test consisted of walking distance of 17 m with people being aware of being measured and then being told to return to the starting position having to walk the same distance but not being aware that they were also being measured back. They found significant differences in the overt and covert measurement, observing that the gait speed decreases and the cadence increases when they are aware of being measured. They conclude that there is Hawthorne effect in gait evaluation and assert that this is because people seek to perform well when they are evaluated.

In addition, Malchow and Fiedler [51] in another study performed a gait analysis in people with lower limb prostheses, in which the objective was to see if the observer affects the results of the experiments. For this, they used some lies in individuals to measure them without feeling that they were observed and the measurements were compared with a formal evaluation. The results allowed to conclude that the effect of the observation exists in the analysis of prosthetic walking because, in the presence of observers, people under study presented changes of their walking pattern in gait speed, stride length, and stride symmetry.

Therefore, it is sought that the collected data have ecological validity, which means that the environment of the experiment, its methods, and materials should approximate the real world [52, 53]. This implies that by guaranteeing ecological validity, the Hawthorne effect is avoided [54]. Thus, ecological assessments are important in determining measurements that have ecological validity.

Wearables, for example, are an approach to ecological assessment, but it is not the only one. Other studies have proposed the use of a markerless system based on depth cameras and ambience devices defined as the use of multiple installed sensors to collect data related individuals in close proximity to them [55].

For example, the study by Auvinet et al. [56] presents a new way to reconstruct the 3D model of a human body from 3 low-cost depth cameras that can recover a body shape in a 3D space in real time that was more accurate than 20 normal cameras.

In addition, in the study by Muñoz et al. [33] that with a device based on Microsoft Kinect is able to sense the movement of each body part of the individual. The motion information of 25 joints is obtained by skeleton tracking provided by Kinect.

Finally, an example of ambience devices is an intelligent carpet developed by Cantoral-Ceballos et al. [57] using plastic optical fiber (POF) that sense bending, quantified by measuring light transmission. The carpet is able to follow real-time the human footprint which allows calculating spatial-temporal variables of gait.

All previous studies would allow a covert assessment because the systems are portable, mountable in a day-to-day scenario, and no need to use markers or something in particular, but simply by being close to the sensors, which implies that the patients would not require knowing that they are being examined.

Considering that ecological validity allows to obtain reliable results, there are methods that allow maximizing the ecological validity of the clinical tests of gait, which can be improved using a test that implies a double task, in which the person must do a concurrent cognitive task or motor while doing the walk test because the situation resembles real-life actions [52, 58].

An example of this strategy is the study by Wang et al. [59] where it was tried to simulate daily activities to know if the use of a circuit of cameras in the home for the continuous care to the elderly is feasible. The experiment consisted in that patients should move in a scenario that looks like a house, doing daily tasks such as opening the door, sitting on the sofa or stand up, and looking for objects and compare the gait variables extracted from the experiment with clinical assessments. The variables that were measured were gait speed, step length, and step time and were measured during the lapses in which the people are walking in the scenario. The researchers found that there are significant differences in gait parameters between continuous onstage monitoring and clinical trials, which led them to conclude that the clinical trials show Hawthorne effect.

Taking into consideration that ecological validity is important for the evaluation of the gait, in-home survey systems have been developed to monitor and analyze the walking of residents, especially focused on elderly care, sensing people with physiological and pathological aging. The main objective of these survey systems is to prevent and alert falls through algorithms of gait analysis in everyday life, detecting anomalies in the progress of daily activity due to falls; fall-induced injuries are the fifth leading cause of death in older adults [60].

For example, the study by Stone et al. [61] presents a system consisting of a Microsoft Kinect used in depth camera mode, deployed in an assisted living residence for continuous gait analysis. The system allows to measure gait variables continuously to report changes in the resident progress, make fall risk assessments, and detect early anomalies. The system serves to support the tasks of the nurses inside the residence, who can see the reports generated by the system.

5. Future of gait analysis in aging

According to the HealthAge International report, in the year 2015, there were 901 million people aged 60 years or over; by the year 2030, the number will grow to 1.4 billion; and by 2050, reaching nearly 2.1 billion. The "oldest-old" group, people aged 80 years or over, is growing even faster than the number of older persons overall; this represents at least 202 million people in 2030 and approximately 434 million for 2050 [62, 63]. This generates a high interest in researching and developing improvements in current systems that can support and improve the quality of life of the future world population.

As previously mentioned, gait analysis is a process by which a clinical expert performs an objective evaluation of the walk, measuring and generating spatio-temporal variables associated with movements of the lower and upper extremities, posture, and balance. Aging (pathological and physiological) generates changes in the walking pattern, affecting the older population. With the current gait analysis, these conditions can be quantified and obtained, through these variables.

According to the current literature, the main devices to perform this analysis are the gait laboratories (GaitRite or Vicon). Moreover, with the recent technological developments, new devices focused on gait analysis have been developed, such as handles with accelerometers, tracking systems of joints or body segments using cameras, smart templates and force platforms.

In addition to this, with the rise of concepts and technologies such as Internet of things, data science, artificial intelligence, and smart cities and homes, among others, recent developments have focused on contributing to the older population. Such is the case of Roschelle et al. [64], who trained intelligent algorithms through five different sensors (infrared motion, light, humidity, contact, and temperature) and supervision of nurses through telehealth strategies and periodic visits to the smart home for medical assistance (health-assistive smart homes) [64]. This work focuses on assessing the challenges and opportunities generated by information-gathering strategies nurse driven for data analytics. In conclusion, they affirmed that the training of algorithms led by nurses can contribute with tools that allow to monitor and alert about the abnormal state of a group of patients, such as reduction in average activity, slower walk, and increase in the use of bathrooms, without generating daily annoyances or obstructions, since for reasons of privacy, many older adults prefer not to be recorded, with a camera or microphone [64].

Another example is documented by Yacchirema et al., who proposed a system for detection of falls using IoT and machine learning algorithms; this system uses three-axis accelerometers, embedded in a wearable 6LowPan device able to capture in real time the information associated with the movements of the volunteers [65]. However, not only the development of intelligent solutions and low obstruction is enough, it is also necessary to promote the integration of these solutions with the ambient assisted living environment and the work environments of the current aging population [66, 67].

In recent years, the term smart aging was developed, which focuses on promoting care and good aging of the adult population, through ICT technologies, i.e., medical systems and devices, biotechnology, and robotics [62]. This new term will encourage the development of solutions through robotic assistance, such as [68] who proposed a system of rehabilitation of walking supported by a robotic structure (MOPASS), which was tested in patients with 60 or more years, during 5 therapies. The results showed moderate usability and good acceptability. However, a large sample size is necessary to validate and generalize the results obtained [68].

These automated gait analysis systems not only focus on healthy people, many of the systems and current developments contribute to the measurement and diagnosis of patients with different neurodegenerative conditions, such as Parkinson's and Alzheimer's. In the case of Parkinson, Terashima and Saegusa developed a robot-assisted gait training device to support walking rehabilitation for older patients. This device not only focuses on the motor part of the patient, it also contributes to cognitive rehabilitation. The device was evaluated with a Parkinson's patient with episodes of freezing of gait, and the stimuli generated by Lucia, an assistant robot, were effective in breaking freezing. In addition to this, the inclusion of assistant robots allows the clinical expert to focus on the patient's body and gait observation.

Considering the current context of gait analysis, and the recent technological developments focused on wearable and non-obtrusive technologies, the future of gait analysis could focus on the ecological and precise evaluations that allow aging in-place on smart cities or smart homes [69]. This can be obtained through IoT evaluation systems, invisible to the patient, connected with alert and security systems, and that allow diagnosis and decision-making using artificial intelligence algorithms.

6. Conclusions

In this chapter, we have revised not only the normal aging and pathological aging process but also the technical evolution of wearable devices and affordable devices that has been developed for gait analysis, helping physicians and experts in the diagnosis of different conditions which affect gait.

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Conflict of interest

Authors certify that they have NO affiliations with involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements) or nonfinancial interest (such as personal or professional relationships, affiliations, knowledge, or beliefs) in the subject matter discussed in this manuscript.

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