

## Muscle Spindles and Locomotor Control-An Unrecognized Falls Determinant in the Elderly?

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Submitted: 2025, Nov 16; Accepted: 2025, Dec 11; Published: 2025, Dec 17

**Citation:** Marks, R. (2025). Muscle Spindles and Locomotor Control-An Unrecognized Falls Determinant in the Elderly?. *J Emerg Med OA*, 3(2), 01-09.

### Abstract

Historically, evidence muscle spindles might be involved in locomotion was provided by their presence in four-footed animal antigravity muscles associated with posture and locomotion and later shown to be present in all muscles involved in locomotion, including human locomotor and other muscles. In unraveling the complexity of the muscle spindle and its role in human locomotor control it appeared their dysfunction could underpin one explanation for falls that lead to high disability in older adult populations, especially those suffering from muscle atrophy and declining neural control. Herein, after reviewing most of the available evidence linking muscle spindles to normal human locomotion and its control, it appears increasing research evidence points to a possible key role for muscle spindles degeneration or dysfunction in acute as well as secondary falls related injuries and events. We conclude periodic muscle reflex testing of vulnerable older adults may reduce falls risk and emergency room visits. In addition, further benefits may accrue if fallers in the emergency room are examined to establish any ongoing need for sensorimotor rehabilitation and joint protection.

**Keywords:** Aging, Falls, Emergency Room, Locomotion, Muscle Spindles, Prevention

### 1. Background

As well as possible immeasurable suffering and a loss of independence, falls among the older population continue to pose an ever increasing and major health care burden in all aging societies. In addition to their associated healthcare costs, falls injuries among the older adult population continue to be associated with high premature death or fatality rates, while many previously unimpaired elders, who survive this particular injury, may experience post falling-associated non-fatal albeit debilitating mobility and independence losses, including those requiring placements in assisted living centers [1,2]. Predicting who is at risk for falls, and future falls as well as efforts to avert falls is hence a highly important health topic in this respect. Among the risk factors for falls, we believe various forms of sensorimotor deficits that often accompany aging and result in gait disturbances can precede falling incidents and are strong falls determinants in this respect. In particular, sensors known as muscle spindles found in all muscles of locomotion and others are small encapsulated

mechanosensory receptors within skeletal muscle tissue defined to inform the central nervous system about the contractile status of each muscle [3]. In particular, muscle stretch receptors and related sensory information that is accurately conveyed to the central neural networks and limbs is essential for ensuring the emergence of a well coordinated set of locomotor movements plus stable postural outputs that prevent harmful movement generation and undesirable gait adaptations and possible injurious falls.

This is borne out by many studies that have examined the role of muscle spindle inputs in modulating spinal cord central pattern generator outputs to primary muscles, as well as their synergists or examined mechanisms of adaptive walking in the face of varying external perturbations [3-5]. Others have noted that the large array of muscle spindle receptors that provide inputs into the sensorimotor system and that are stretch sensitive also supply the cerebellum, involved in balance control as well having the ability to mediate movement and position sense and coordinated

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movements and that may all fail to protect against falls if degraded [6,7]. The additional rationale for specifically examining the role of the muscle spindle in the context of locomotor control, a well established falls predictor in the active elderly, is its link to a complex set of afferent and efferent pathways that appear to influence muscle tone and contractile behavior and will generally advance any required muscle adjustments or adaptations needed for locomotor movements to be carried out in a timely, low energy cost, and safe way [8-10]. They are not only implicated in reflex actions and the control of muscle stretch sensitivity via its motor innervation links and adaptively important sensory motor control brain and spinal cord links and mechanisms, but also those that appear to have input-output linkages that foster the ability to 'smooth' out unwanted irregularities in movement trajectories during bipedal locomotion [4,11].

Conversely, deafferentation that can occur in degenerative joint conditions such as osteoarthritis and its adverse implications for muscle reactivity and well modulated motor responses is a situation that potentially engenders abnormal locomotor movement patterns and non rhythmic responses that could predispose to falls [12]. Indeed, as one key sensory modality, the muscle spindle array and its density and integrity now appears essential for ensuring gait will be self organizing and optimally emergent without any risk of falling. Yet, in the population most affected by falls incidents and risk, older adults who may well undergo declines in their dynamic sensitivity to muscle stretch may lose their ability to generate well coordinated locomotor movements, and allied or supportive functions [13]. That is, while their intricate connections appear to provide the spinal cord central pattern generator responsible in part for locomotion with timely information about unexpected external conditions, thus enabling an organism to produce accurate, stable, and timely outputs for the limbs in the face of ever-changing environments, and terrains, the failure of this mechanism may prove devastating in the face of unanticipated perturbations [8,14-16].

Nevertheless, although clearly salient in the hierarchy and output of motor commands and response mechanisms, muscle spindles that serve as key sensorimotor proprioceptors are usually ignored during examination and analysis of the causes of these among many older fallers and especially when designing therapeutic strategies for averting this injury in the face of any neurological disease [16]. However, injury as a result of tripping alone is relatively common among older people, even if deemed healthy, and is one where risk is increased with fatigue, muscle atrophy, and delayed or suboptimal muscle receptor afferent inputs and poorly modulated ability to ensure the foot clears the ground during the swing phase of walking as a result [17,18]. In sum, consistent with the needs of the organism, muscle spindles and their sensory nerve endings that provide length- and position-dependent sensory inputs to the spinal cord and central nervous system appear to be highly important stretch sensitive structures in the context of locomotor control.

However, very few links have been made between these highly complex structures and their functional diversity and salient neural role in the context of falls injuries incurred often during walking, even though it can be shown the complete loss of muscle spindles appears to seriously compromise the regularity of locomotion and the associated step cycle, as well as balance if its cerebella inputs are impaired [19-21].

That is, although the presence of any dysfunction in the muscle spindle and/or its neural pathways could consequently be expected to produce gait disturbances or suboptimal placements of the foot that could lead to a loss of adaptive walking that leads to falls, few attempts have been made in general to elucidate and report on a distinct role for muscle sensory receptors in the context of falls injuries that mostly occur due to slipping or tripping. As a result, although independent studies on muscle spindles and their varied functions are quite numerous, the clinical implications derived from these studies for advancing falls injury prevention and identifying subject risk is highly limited.

## 2. Methods

To provide some insight into whether falls injuries incurred during walking may be ascribed in selected cases to deficiencies in the muscle spindle structures and/or their diverse neural connections, data housed in key repositories were searched and examined. The key topics sought were related to the role of muscle spindles in the control of intralimb and interlimb movement patterns during gait, and whether muscle spindles are further implicated in providing deficits and contractile mechanisms stability during the stance phase of the gait cycle and may result in a fall if they fail to function.

The specific themes examined were:

- Whether muscle spindles have an impact on falls risk in the elderly.
- Whether older adults with muscle receptor deficits will be at high risk for falls, but that can be targeted successfully
- Whether muscle spindles have an impact on locomotion in the elderly and by analogy on falls risk.

Excluded from the detailed descriptive analysis were studies of subjects younger than 60 years of age, those focusing on neurological diseases, studies conducted in a language other than English or were proposals or incomplete articles. The studies presently reviewed included observational, as well as prospective or case controlled studies on any substrate, with an emphasis on those published between January 1 2000 and December 31 2025. The review is largely limited to studies conducted in health centers or the community, rather than the nursing home or residential setting as the goal was to derive implications for community dwelling older adults who wish to remain independent in their own homes but may fall and be sent to emergency rooms.

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### 3. Results

#### 3.1 Major Findings

The literature search revealed increasing numbers of works dealing with muscle spindles and aspects of locomotion and more recently with falls and fall injuries specifically. Regarding muscle spindles and their effects, several studies supported the view that muscle spindle inputs are helpful in resetting the normal locomotor pattern in times of perturbation because they are able to convey ongoing information about the magnitude and rate of muscle stretch to interneurons and motoneurons, but their failure may lead to increasing challenges in the day to day ability of the organism to walk safely and without effort [22,23].

Among the numerous citations detailing some aspect of falls injuries and/or falls injury determinants in the older adult population that have been housed over time there is general agreement on several key risk factors including:

- Impairments in cognitive function and postural reflexes.
- Dizziness, pain, selected pain/psychoactive medications, and visual impairments.
- Vestibular and various co-morbid disorders such as diabetes.
- Reduced muscular strength and endurance.
- Impaired gait, and poor balance.

Loeb and Hoffer suggested however, that it is muscle spindle afferent inputs that are of high import to recognize as falls determinants or mediators as they have a major role to play in the control of locomotion and the generation of smooth energy efficient automatic movements as well as in response to perturbations [22]. More specifically, this group found the extensor or anti-gravity muscles, which are mostly active while lengthening or when the muscle is contracting nearly isometrically are able to produce muscle spindle afferent inputs that result in an energy-efficient mechanism for the generation of large forces with a low work output. Loeb and Hoffer deemed this mechanism to be consistent with the need of the organism to maintain a non-accelerating forward motion, in which the body weight must be transferred from side to side, but is able to be modulated to accommodate applied loads and their rates of change with changes in gait speed. In contrast, muscle spindles in the flexors which were usually deemed to shorten actively and rapidly against minimum loads such the inertial mass of the limbs were said to foster a relatively constant motor pattern, rather than a changeable one, because they were found much less dependent on gait speed than the extensors.

Deng et al. propose muscle afferents when stretched or experiencing tension changes can activate antagonistic muscle pairs about each joint in the sagittal plane when intact [23]. This system works effectively to influence the setting and spinal circuits involved in regular or perturbed walking control motions, but may be altered in the face of any prevailing deafferentation associated situation and the impact of age on muscle afferent structures and function. However, where present the powerful role of muscle spindles in

locomotor control is consistently evidenced in fictive preparation studies, where sustained stimulation is applied to brainstem mesencephalic locomotor region in decerebrate animals. These tend to suggest that during the extension phase of locomotion, disynaptic reflexes evoked from group I ankle extensor muscle afferents simultaneously activated hip, knee and ankle extensor motoneurons, thus increasing force production necessary to support the body during stance [24]. Moreover, consistent with the idea that muscle spindles are highly implicated in locomotor control efforts, data reveal they can enhance and reset locomotor activity patterns, stimulate or impact the relationship between spinal proprioceptive input patterns and neuromuscular control strategies of leg muscle spindles and hence serve to modulate locomotor phase duration, as well as speed, and gait stability [25-27].

Research also shows that muscle spindles enable the organism to carry out reciprocal movements in a timely way, while providing the central nervous system with an up dated set of inputs during on-going activities that may not only be crucial for producing optimal stability, but also for exhibiting resistance to obstacles placed in the walker's path [27-29]. In this regard, muscle spindles must however be able to sense limb position accurately, the nature of any prevailing muscle movement or non movement, and desired movement speed factors that underpin the desired movement or non movement of a limb during reciprocal walking to avert any falls risk [28]. That is, muscle spindles must be able to sense as well as provide well modulated timely neural inputs and linkages that must be recalibrated as indicated, for example if a slippery surface is encountered to avert harm and destabilization and provide the optimal degree of kinaesthesia and control of bodily movements and spinal motoneuron pathways that determine contraction responses [30-35]. The sensory information that can thus activate muscle synergies in a coordinated way or may fail to do this or produce stable walking in the older adult if muscle spindles are degraded by age [13]. If so, the locomotor muscles usually activated to prevent falling may fail to do so in a timely protective manner [8,10].

Alternately, to avert walking challengess, muscle spindle inputs and outputs must be physiologically able and primed effectively in a timely manner. to avert both fatal and nonfatal injuries, a significant source of morbidity and mortality often leading to a rapid downward spiral in multiple systems, including the musculoskeletal system, the central nervous and sensory systems [36]. Fallers who experience a loss of independence may be forced into nursing home admittance and a low life quality. As well, fearfulness of falling in the future might cause social withdrawal and disengagement, in addition to imposing a heavy social and financial strain on the fallers' family, community health services, and economy [36]. Reducing the magnitude of falls injuries and their consequences is indeed a key geriatric health issue and one where several convergent influences might impact the timely

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function of reactive muscle responses during gait that lead to falls. These factors include, but are not limited to deficient muscle strength, confusion, sensory losses, poor postural control or balance impairments, especially in those of higher ages [1-3,6,35,36]. However, despite efforts to offset falls risk among the elderly, the specific mediating influence of the motor system efferent and afferent pathways embedded in extensive numbers of muscles subject to aging and muscle mass losses remains understudied and relatively unacknowledged [6].

That is, despite a converging research base that implies optimal muscle spindle function potentially impacts locomotor control profoundly and may be helpful or even crucial in offsetting falls risk among the elderly in the face of locomotor challenges, this idea remains a topic that is rarely studied with regard to the influence of proprioceptive factors on balance capacity in general in the older adult population [8]. Before continuing to base public health as well as private practitioner falls prevention recommendations on inconsistent or incomplete consideration of research findings, it is our view that many problems associated with falls, and their meager intervention outcomes can benefit from a current review of muscle spindle related literature and insights. In particular, they can be applied to potentially understand and thereby offset falls risk in the aging adult, thus helping to avoid management errors and omissions that could be highly costly to the individual as well as society, such as oversight of muscle spindles and their importance in the context of locomotion and stepping in health as well as disease contexts [37-40].

In one recent study designed to establish a proprioceptive feedback framework to depict spinal proprioceptive input patterns and neuromuscular control strategies in cases with knee osteoarthritis a musculoskeletal model developed to estimate muscle and tendon organ afferent activities at the spinal L1-S2 levels showed that enhancing proprioception feedback can have a significant effect on spinal inputs that govern locomotor control and that could potentially be harnessed clinically [41]. Moreover, falls could be explained and averted by accounting for the fact that those muscle spindles provide the CNS with information about the condition of the limb directly involved in movement as well as adjacent joint sites [42].

#### 4. Discussion

Many decades of study have shown muscle spindles, the most commonly observed sensory structure located in mammalian muscles constitute a key group of proprioceptors underpinning somatosensory signaling and transduction and its impact on movement synergies within the locomotor system [3,10,14]. However, this inherent protective and functional motor control system can be subjected to many degrading influences [2,40]. Indeed, adverse kinematic and kinetic profiles have been demonstrated in multiple locomotor simulation models if muscle spindle networks are rendered dysfunctional, disrupted or destroyed artificially or by injury, or disease [3]. Insofar as

this situation would have implications for the prevention and rehabilitation of many locomotor disorders, spindle afferent inputs in the osteoarthritic model alone could explain a fair number of falls experienced by those with knee joint disease and could be helpful for understanding those falls processes amenable to intervention, such as muscle weakness and atrophy. In addition, especially in the face of competing stimuli, muscle fatigue may decrease spindle stretch sensitivity and optimal response timing and muscle stabilizing synergies.

Age related pathological muscle and nerve structural changes are also likely to alter normal reciprocal patterning of the leg muscles during locomotor behavior as well as the ability to detect departures from the trajectory of the anticipated movement. Moreover, the individual may be less able to produce the degree of coordination required during locomotion to successfully prevent a subsequent slip or trip. They may hence be quite prone to multiple injurious fall incidents when walking, especially out of doors, or if the interior is unfamiliar or an external barrier to safe locomotion. When faced with unexpected obstacles, or unanticipated changes in the ground surface of stairs they are even more likely to encounter falls that are injurious if they cannot activate the required compensatory strategies in a timely and force-efficient manner. In particular, any subnormal or delayed interaction between muscle afferent inputs, their links to the brain or spinal cord and subsequent subnormal outputs during gait coupled with muscle weakness may have multiple cascading adverse effects on locomotion, in general, and on preserving muscle synergies that are designed for stabilizing purposes. For example, the individual may adopt a slower than desirable gait speed, which increases the chances of slipping, tripping and falling, among other gait disturbances, especially if vision or cognition or both are impaired [43-50].

Indeed, recent experimental manipulations have shown that information from the foot sole alone can have a widespread influence on balance, proprioceptive information, and gait. However, these interactions are not linear or easy to reverse because any generated reflex response to a balance perturbation implicates both the spinal and supra-spinal neural sites where sensory feedback is modulated. Additionally, other muscles, notably those of the neck and trunk that contribute to kinaesthesia and the sense of orientation in space can be diminished in the face of age-related afferent input declines and density plus muscle strength losses, as can disruptions at the neuromuscular junction, and sarcopenia, muscle feedback and innervation mechanisms and compensation strategies critical for the control of upright posture, and safe walking ability. Declines in balance during standing and walking as well as defects in proprioception may thus be anticipated and need to be identified and treated proactively, rather than reactively to avoid altered muscle spindle derived proprioceptive signaling emergent motor programming deficits due to erroneous stimuli interpretations and impairing transmission capacity as well as related altered spindle anatomy as well as function, and poor position sense, direction plus speed attributes and impaired stretch and tension sensitivity

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[51-60].

According to Ito et al. reduced proprioception including that due to muscle spindle deficits do tend to affect fall risk in the elderly, for example those who present with lumbar spondylosis and a decrease in trunk proprioception or lower leg impairments or both that may foster a decline in desirable sensory motor processes that can ensure postural stability [61]. In comparing a group of no-falls-risk adults, their results showed the fall-risk group displayed a high relative lumbar spine proprioceptive weighting ratios that was possibly due to the over-dependence on inputs from muscle spindles in the calf muscles. Indeed, findings over time do tend to affirm a key role for muscle spindles in maintaining locomotor functions, and to assert neural control adaptations despite perturbations or obstacles. Data specifically show that sensory feedback from group Ia/II muscle spindle afferents regulate motor function and control in normal and perturbed walking. These sensory units that are speed and length sensitive can be readily impaired in later life [4, 62-67].

Applying this knowledge about the highly vital role of the muscle sensory system in gait control can potentially help us understand a generally unrecognized falls determinant that may prevail in vulnerable older adults. To this end, more careful neural based analyses and the use of AI and other diagnostics in this regard applied for purposes of dynamic postural control screening and possible falls risk reduction interventions appear indicated [41,42,68-74]. Exploring the nature of the mechanosensitive ion channel ASIC2 as a key component in proprioceptive sensing and regulation of spine alignment and the impact of muscle morphology on muscle afferent sensibility is also indicated [75,76]. This is because it seems likely that efforts designed to normalize and maximize deficient muscle spindle inputs in both lower limb extensor and flexor muscle groups where these are dysfunctional or weakened so as to secure optimal control actions will prove helpful in the overall approach to falls prevention among the elderly than the presence of incomplete information and erroneous computation externally as well as internally. This is because the sensory system is likely to be essential for optimal rhythmic and stable timely forward motion in day to day life encounters.

However in the aging individual with a declining neuromuscular system, locomotor training or efforts to maximize sensorimotor integration and balance during gait may prove be required to facilitate or retrain or introduce appropriate muscle activation patterns, and possibly their response time and stabilizing functions. Sensorimotor training may also benefit balance control during walking under differing environmental constraints, possibly preventing the incidence and magnitude of some fall injuries attributable to misstepping when walking, and their detrimental consequences [41]. As stated many years ago by Pearson, inherent muscle afferent feedback mechanisms not only contribute to the ability to walk normally, but more particularly help to foster appropriate adaptations during different walking conditions or

precision tasks [12]. As outlined in this brief, evidence continues to show muscle spindles are important because their inputs are necessary for stable walking, and because accurate movements require a precise match between mechanical muscle properties and properties of the muscle's physical environment [6]. Since these properties can change, adaptive mechanisms that can optimize muscle activation patterns may be efficacious and hence essential to contemplate and enact [12,77].

At the knee for example, sensory afferents originating from knee joint receptors provide the nervous system with information about the internal state of the joint and these sensory signals are used to modulate the co variations among the activity of the spinal cord and a subset of vasti muscles and others across strides of locomotion. Where they are damaged or compromised resultant subnormal muscle spindle stretch sensitivity and inputs and their impact on output motor effects such as muscle reflexes potentially fosters abnormal motor and locomotor efficacy and thereby may foster a heightened fall risk and progressive increases in fall occurrences, severity and disease manifestations in vulnerable older adults, especially if undetected and untreated [6,38]. Since falls associated with osteoarthritis alone can magnify or induce a life time of suffering, it appears salient to uncover if more emphasis should be placed on possible preventable health associations such as muscle sensitivity. Moreover, if preventive strategies do exist they should be grounded in a strong cumulative solid evidence base, such as that presented here in summary.

## 5. Concluding Remarks

While we can provide no definitive data linking some falls injuries in the older adult to muscle related sensibility attributes and their modulation during gait, and many design issues prevail, until more research data emerges, our decade's long extensive and intensive evaluation and analysis leads us to conclude:

- Muscle spindle units and associated input and output pathways strongly regulate an intricate integrated network of sensorimotor functions and responses that not only determine in part the efficacy of the central nervous system, spinal, and motor control feedback, but the quality and efficiency of feed forward networks and locomotor stability mechanisms.
- Effective locomotor adaptations clearly depend on the integrity of the reactivity and sensitivity of the muscle afferents embedded in the primary locomotor implicated muscles.
- All phases of the gait cycle, including stance and swing, plus inter limb coordination appear to be influenced by the length, velocity and stretch sensitivity of muscle spindle afferents, their response efficacy, as well as the state of the final gamma motoneurone pathway and muscle status that controls the emergent muscle responses.
- Deafferentation, perturbations, or defects in any realm of these neural processes may explain an inability to respond protectively when walking, as well as the presence of a heightened fall risk

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in an individual of high age as well as those with neuromuscular deficiencies and others.

- To enhance our understanding of the nature of human locomotion and its association with falls injuries among older adults and others, more evidence that links muscle spindle activity to locomotion in the human aging population in ecological settings as opposed to the laboratory setting and the study of subhuman non bipedal gait.

- Timely targeted falls prevention efforts that acknowledge the key role of the neurosensory system and its adaptive potential may help avert immense suffering, hospital and societal costs, and premature death rates, while fostering injury recovery, where and when necessary.

## 6. Health Implications

Falls and their immense adverse impacts continue to increase unabated in both incidence and prevalence, and as such remain a widespread costly health concern and one markedly impairing life quality in later life, despite years of research and programs to avert this in older adult communities. Not only are falls commonly associated with the onset or perpetuation of longstanding pain, disability, independence losses, and premature deaths for many, but the outlook for older adults in this regard, remains bleak unless due action is taken to avert this public health challenge. This in our view demands more insights into falls causative factors and their application to targeted management or mitigation strategies that can offset the risk for falling among the elderly. Based on our analysis and many years of related study we believe programs currently advocated to help the aging individual to avoid the partial or complete loss of personal freedom associated with falls, as well as excess rates of premature mortality, and morbidity, must in our view account for the role of muscle spindle networks and their integrity or face failure in finding appropriate strategies to prevent falls injuries due to unstable gait or unanticipated environmental encounters.

Clinicians can possibly help by conducting brief sensory motor tests and a brief history of falling and modes thereof at the bedside and recommend further steps without delay. AI diagnostics can be used to discern muscle structural anomalies and their medical record can reveal medication intakes and disease status. They can then recommend follow up home visits and educational and rehabilitation opportunities as indicated. Active older persons with marked lumbar spine degeneration as well as knee instability who are obese or sarcopenic and depend on opioids should be especially targeted [78].

## Acknowledgements

None

## Conflicts of Interest

None

## Funding

None

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