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Review Article

The Role of Neuromuscular Changes in Aging and Knee Osteoarthritis on Dynamic Postural Control

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ABSTRACT: Knee osteoarthritis (OA) is a chronic joint condition, with 30% of those over the age of 75 exhibiting severe radiographic disease. Nearly 50% of those with knee OA have experienced a fall in the past year. Falls are a considerable public health concern, with a high risk of serious injury and a significant socioeconomic impact. The ability to defend against a fall relies on adequate dynamic postural control, and alterations in dynamic postural control are seen with normal aging. Neuromuscular changes associated with aging may be responsible for some of these alterations in dynamic postural control. Even greater neuromuscular deficits, which may impact dynamic postural control and the ability to defend against a fall, are seen in people with knee OA. There is little evidence to date on how knee OA affects the ability to respond to and defend against falls and the neuromuscular changes that contribute to balance deficits. As a result, this review will: summarize the key characteristics of postural responses to an external perturbation, highlight the changes in dynamic postural control seen with normal aging, review the neuromuscular changes associated with aging that have known and possible effects on dynamic postural control, and summarize the neuromuscular changes and balance problems in knee OA. Future research to better understand the role of neuromuscular changes in knee OA and their effect on dynamic postural control will be suggested. Such an understanding is critical to the successful creation and implementation of fall prevention and treatment programs, in order to reduce the excessive risk of falling in knee OA.

Key words: Knee osteoarthritis, balance, postural control, neuromuscular, aging

Osteoarthritis (OA) is a chronic joint condition that affects one in ten adults [1]. This is a costly condition – over one quarter of the total cost of musculoskeletal diseases in Canada is attributed to arthritis, for an estimated 6.4 billion dollars every year [2]. In the United States, the cost is approximately 10 times greater, estimated at 65 billion dollars a year [3]. Of the known types of arthritis, OA is the most prevalent [2], and the knee is the joint most commonly affected. OA increases in prevalence with age, with 30% of those over the age of 75 exhibiting severe radiographic disease [4]. OA results in a loss of physical function, with a significant toll on quality of life [4]. OA is also associated with an increased risk of falling, with fall rates reported in up to 50% of individuals with OA, compared to 30% of healthy older adults.

Falls in older adults, with and without OA, are a considerable public health concern. Among those 65 and older, falls are the leading cause of acute injury [5,6] and research has shown that 32% of those experiencing a fall will require help with activities of daily living after falling, severely limiting mobility and independence [7]. Previous studies have highlighted the high incidence of falls in samples of elderly individuals with OA – over 50% [8-10]. Those with knee OA are at a higher risk of falls than healthy elderly individuals, as measured by the

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Physiological Profile Assessment, a battery of tests measuring risk factors for falling [8,11]. Compounding this is a greater fear of falls in individuals with knee OA compared to healthy controls [8]. While normal aging is associated with neuromuscular changes, even greater neuromuscular deficits are seen in musculoskeletal conditions including knee OA. These neuromuscular changes may contribute to the high rate of falls experienced by those with OA. Therefore, it is important to understand how balance is influenced by the neurophysiological changes associated with normal aging, as well as those changes which are specific to OA.

There is little evidence to date on how knee OA affects the ability to respond to and defend against falls and the neuromuscular changes that contribute to balance deficits. To address this gap, the following review will:

1) Highlight key characteristics of balance responses to falls and fall circumstances

2) Review known changes in postural control with normal aging

3) Identify neuromuscular changes with aging and evidence supporting their effect on postural control

4) Review balance problems and neuromuscular changes in knee OA. This will highlight neuromuscular changes in those with knee OA beyond the changes seen with normal aging, in order to better understand the current evidence surrounding the origins of balance problems in knee OA

Key Characteristics of Postural Responses

The ability to maintain dynamic postural control is a key element of physical function necessary for mobility and independent living [12]. Postural control involves maintaining the centre of mass (COM) within the base of support (BOS) [13]. Dynamic postural control refers to the ability to actively regulate the position of the body by responding to postural perturbations [14] such as trips, slips, and bumps, and is necessary to recover from unexpected perturbations experienced in the environment. In a laboratory environment, external perturbations are often created by moving or tilting the surface of a platform on which the individual stands, by pulling on a cable attached to the person, or by having the individual lean while being suspended by a cable and releasing the cable [15]. There are two possible postural responses to these external perturbations: the motion of the COM can be controlled by generating muscle torque while maintaining the BOS (called feet-in-place responses), or the BOS can be altered to maintain the COM within its bounds by taking a step or grasping a support such as a handrail (called change-in-support responses) [13].

Impairments in dynamic postural control with aging and the increased risk of falling highlight the importance of dynamic postural control strategies in navigating the environment and avoiding falls. Previous research has shown a significant positive correlation between dynamic postural control measures (involving both feet-in-place and change in support strategies) and increased fall risk [16,17]. While measures of dynamic postural control are not infallible predictors of falls risk [18], there are advantages to assessing dynamic postural control, such as the ability to standardize the type and magnitude of postural perturbations [14], that make dynamic postural control an ideal target for examining the ability to defend against a fall.

The successful response to a postural perturbation can be divided into 1) kinematic and kinetic responses, and 2) muscular responses. Kinematics – the analysis of movement of the body, and kinetics – the analysis of forces and joint moments [15] provide important information about movement strategy and the net torque forming the postural response, respectively. Kinematic and kinetic responses can further be separated into passive and active phases of the response [19]. The passive phase reflects the initial body movements, and torques, generated by the perturbation as it acts on the body. The subsequent active phase involves stabilizing movements and torques that are initiated by the CNS to counter the initial perturbation-induced passive movements. For example, a toes-up rotational perturbation (where the platform rotates posteriorly), causes the lower legs to be rotated backward, requiring an active muscular response in the tibialis anterior muscle to generate sufficient dorsi-flexion torque to arrest and reverse the lower leg movement.

Along with kinematics and kinetics, the muscle response to perturbation can be analyzed using electromyography (EMG). Muscular responses to perturbation can be divided into a short latency (stretch) response, an automatic postural response, and a voluntary postural response. The stretch response is elicited by muscle length changes caused by the initial perturbation [15]. This reflex response is often destabilizing during rotational perturbations, but is assistive during horizontal translations. The automatic postural response is considered a balance-correcting response [19] that occurs with a latency that is considered too late for a simple spinal reflex, yet too early for a voluntary response. For instance, in reaction to a toes-up platform rotation, the largest automatic response in the (stabilizing) tibialis anterior muscle occurs between 120 – 220 ms [19]. Finally, the voluntary postural response falls fully within the bounds of voluntary control (350 – 500 ms and on). During this phase, muscle activity continues and tends to be stabilizing, such as tibialis anterior and quadriceps muscle activity after a toes-up platform rotation [19].

For all phases of muscle activity – short latency, automatic postural response, and voluntary postural response – three factors must be considered. The onset, amplitude, and coordination of the muscle activity are key characteristics of the muscular response that facilitate comparison across postural responses and describe the overall reaction to perturbation. The onset of the muscular response is particularly important, as delays in muscular activity can have a significant impact on the overall response to perturbation, including the ability to successfully maintain postural control [20]. Response amplitude, appropriate to the magnitude of the perturbation, is also important for defending against a fall. For instance, attenuated muscle response amplitudes may signify an insufficient reaction to a perturbation, which could result in a fall [21]. Finally, the coordination of muscle activity, which could be defined as the pattern of activation and muscle response amplitude across muscles in response to a postural perturbation, is also critical.

Postural Control and Aging

1) Feet-in-place responses:

With age, significant changes in the kinematic, kinetic, and muscular response to perturbations have been observed. A summary of the postural response characteristics that may be altered with age is presented in Table 1. The immediate kinematic response is affected by age; elderly individuals exhibit reduced movement of the body in reaction to a perturbation. For instance, the passive trunk movements are small, and in the same direction as the perturbation in older adults, compared to large trunk movements in young adults that are directed opposite to the perturbation direction [21]. This initial biomechanical change interferes with early compensatory trunk movement, and has been hypothesized to be due to stiffness of the trunk. Trunk stiffness may also account for the greater acceleration of the head in the direction opposite to the platform rotation [21]. Arm movement in older adults is in the same direction as the perturbation, a reaction that is again opposite to arm movements of young and middle-aged adults [21]. This altered reaching strategy may be used in an attempt to reach or grasp objects in the direction of the fall; however this increases the center of gravity displacement, and may increase the likelihood of a fall if a handhold is not reached. The active kinematic and kinetic response is also altered. For instance, ankle torque in response to perturbation is larger in older adults compared to younger controls, suggesting an inappropriate and perhaps unnecessary size of reaction, to the perturbation [21]. Along with these altered kinetic responses, older adults exhibit a higher frequency of loss of balance [22,23].

The effect of age on short latency responses to perturbations are minimal; there have been some reports of small delays in lower-leg stretch reflexes to platform rotations [24], and no observable changes in amplitude or coordination of these stretch responses.

Table 1. Summary of response to perturbation characteristics that may be affected by aging

Perturbation Response		**Associated Changes with Age**
Kinematic & Kinetic	Passive-induced responses	Yes[21]
	Active-induced responses	Yes[21,29,31-34]
Muscular Response		
Stretch Response	Onset	Yes (Minimal) [24]
	Amplitude	No
	Coordination	No
Automatic Postural Response	Onset	Yes[21,24-26,29,34]
	Amplitude	Yes[21,24,26,30]
	Coordination	Yes[33]
Voluntary Postural Response	Onset	Yes[29,34]
	Amplitude	Yes[28]
	Coordination	No

‘Yes’ denotes known differences between young and old individuals for each aspect of postural control, with references in superscript. ‘No’ denotes no known differences between young and old adults.

In contrast to short latency responses, automatic postural responses do differ between young and older adults. Automatic postural responses to perturbations in elderly individuals are delayed and reduced in amplitude in both distal (soleus and tibialis anterior), and proximal (gluteus medius) muscles [21,24-27]. The delayed and decreased amplitude of postural responses affect the ability to react to postural disturbances, particularly larger perturbations that require greater muscle responses. In contrast, the coordination of automatic postural responses are not affected by age. For instance, the pattern of muscle activity in response to perturbation appears to remain unchanged with age [28]. Further, no increase in co-contraction, a measure of response incoordination, has been noted with age [28].

Some (but not all) aspects of the voluntary postural response to perturbation are also altered in elderly individuals. While no differences have been noted in response onset [28], there may be an increase in the amplitude of muscle activity. Increased amplitude of the voluntary postural response has been noted in the tibialis anterior in response to perturbation [28], however this increase is not seen in other muscles such as the paraspinals or gluteals [21]. This increase in muscle activity in tibialis anterior may come as compensation for the reduced muscle activity seen in the stabilizing muscles during the automatic postural response. Coordination of voluntary muscle activity remains unchanged – Allum et al [21] found no difference between young and old individuals in the pattern of hip and trunk muscle activity at different orientations of platform rotation.

2) Change-in-support responses

When individuals respond to a perturbation by stepping or grasping a handhold (change-in-support reactions), further differences are seen between young and old individuals. The immediate kinematic response, prior to the step, has been described above. Following this, the kinematic and kinetic response is delayed, and the movement pattern is altered. For instance, older adults take longer to initiate foot off, and to contact the ground again [29]; however this difference with age has been disputed [30]. These contradictory results could be due to study differences in perturbation method (cable pull, platform movement) and predictability of the perturbation. Older adults also tend to a) initiate stepping responses at lower levels of instability, [31], b) have a reduced ability to generate torque at a sufficient speed to recover balance, particularly when released from a forward lean position with a large lean angle [32], and c) are twice as likely as young adults to take additional steps to regain stability, particularly in the lateral direction [29,33]. Older adults favour multiple side-steps [33], whereas young adults tend to use a single crossover step to recover stability. The cross-over step is a more complex step and requires single-limb support for a longer period of time [33], aspects that may make this maneuver more difficult for elderly individuals and may contribute to why the strategy is used less often by older adults. The complexity of stepping in response to perturbation is highlighted by the greater number of limb collisions during the response by older adults [29]. Stepping has been observed in 35-45% of falls or near falls [13].

Older adults are more likely to initiate grasping movements than young adults in response to perturbation [33]. While doing so, older adults are more likely to sustain hand-handhold collisions, use the arm opposite to the handhold to reach, and to reach with both arms [34]. These changes in kinematics increase the risk of falling, for instance, by reducing the probability that the individual will successfully grasp the handhold when they are reaching with the arm that is farther away from the handhold. Grasping reactions become more common with age, but are not always successful in regaining postural control – arm responses have been observed in 65-75% of falls and near falls [13].

Muscle responses when stepping may be different between young and old individuals. Changes in the stretch response, prior to the step, are few and have been described above. Automatic postural response differences between young and old in onset and amplitude of muscle response are present, and particularly evident in the arms. No difference in onset latency of muscle activity has been found by some [35], but other studies show delays in tibialis anterior and gastrocnemius EMG onset latency with perturbation [29]. The onset latency of biceps and deltoid muscle activity is increased in older adults when grasping [34,36]. No difference in lower leg muscle response amplitude is noted [37], but a clear dampening of the arm muscle response [30] is seen. As movement of the upper body is common and often necessary to prevent falling (by grasping a handhold, for example), delays in muscle response and dampened muscle activity can affect the ability to defend against falls. Muscle coordination is also affected – there are differences in muscle activation patterns, largely dependent on the stepping strategy chosen (single cross-over or multiple side steps) [33].

In summary, the greatest alterations with age in responding to a fall are seen during automatic and voluntary postural responses, with little differences noted in short latency responses, which may be due to the different origin of these responses [19,21]. While significant impairments in dynamic postural control in all areas of these responses – kinematics, kinetics and muscular response – are noted, the causes of these deficits are not always clear. It has been hypothesized that particular neuromuscular changes with aging could increase the risk of falling by causing changes in kinematic, kinetic, automatic and voluntary postural responses [20,38].

Neuromuscular Changes and Aging

Many neuromuscular changes have been associated with aging. Not all neuromuscular changes associated with aging have been investigated directly to determine their effect on postural control. The neuromuscular changes that have been linked directly to dynamic postural control will be reviewed first. These neuromuscular changes are often directly investigated in comparisons of young adults, and are listed in Table 2. Neuromuscular alterations that are hypothesized to have an effect on dynamic postural control but are not currently directly linked to changes in postural control will then be reviewed.

Table 2. Summary of known neuromuscular changes with aging and their effect on dynamic postural control

Neuromuscular Changes with Age	Kinematic and Kinetic Response		Automatic Postural Response			Voluntary Postural Response		
	Passive-Induced Responses	Active-Correcting Responses	Onset	Amplitude	Coordination	Onset	Amplitude	Coordination
Proprioception	Yes[20]	Yes[44]	Yes[20,44]	Yes[20]	No	No	No	No
Vestibular Input	No	Yes[38,47]	Yes[38]	Yes[38,49-51]	Yes[38]	No	Yes[38]	Yes[52]
Vision	No	Yes[34]	No	Yes[19,57]	No	Yes[56]	No	No
Muscle Strength	No	Yes[73-75]	No	Yes[73]	No	No	Yes[73]	No
Muscle Power	No	Yes[80]	No	No	No	No	No	No
Muscle Fatigue	No	Yes[83,85]	Yes[86]	Yes[86]	Yes[86]	No	No	No

'Yes' indicates aspects of postural control affected by the neuromuscular factor listed, with references in superscript. 'No' is indicative of no effect of that neuromuscular factor on the aspect of postural control in question.

1) Proprioception

Reductions in proprioception are associated with increasing age. In particular, reduced plantar pressure cutaneous sensation [39,40], poor vibration sense [41], and reduced joint proprioception, as measured by knee joint position sense [42] have all been noted with age. Proprioceptive changes directly affect postural responses to perturbation. For instance, a reduction of plantar pressure cutaneous sensation and vibration sense (aspects of proprioception) due to limb cooling results in an increase in the degree to which the COM approaches the base of support limit posteriorly before stepping is initiated (foot off) [43]. An increase in the number of responses where multiple steps are used during forward stepping, and an increase in multiple side steps instead of cross over steps during lateral perturbation [43] have also been noted. These kinematic changes are similar to the alterations seen with age, and are indicative of reduced control of weight transfer during stepping, a necessary part of change-in-support postural strategies.

When joint proprioception is lost, kinematic, kinetic, and automatic postural muscle responses are all affected. Ankle torque onset is delayed in patients with lower leg proprioceptive loss [44]. The movement pattern in response to perturbation is affected – trunk roll movement of a total leg proprioceptive loss patient is in the direction of the perturbation, opposite the response of healthy individuals [20]. Interestingly, a similar change in movement pattern is also seen in normal aging, which may interfere with early compensatory responses and has been hypothesized to be due to trunk stiffness.

Automatic postural responses are delayed in total leg proprioceptive loss, while this delay is not seen in individuals with lower leg proprioceptive loss who have intact trunk and hip proprioception [20,44]. Thus, loss of proprioception in proximal joints may partly be responsible for the delays in stabilizing muscle response (for instance, in the tibialis anterior during toes up rotational perturbations). This may also be the case for reductions in the amplitude of the muscle response. A greater reduction in the amplitude of automatic postural responses (in all muscles except the quadriceps) is seen in total leg proprioceptive loss, more so than lower leg proprioceptive loss patients and healthy controls [20]. The role of proprioception in proximal joints in generating automatic postural responses is supported further by the lack of effect of nulled ankle inputs on automatic postural response onset and amplitude [20]. Nulled ankle input refers to controlling the rotation and translation of the platform in order to keep the position of the ankle constant, thus removing ankle position information during perturbation. However, a loss of joint proprioception does not seem to affect the coordination of muscle activity. For instance, paraspinal muscle response patterns are similar in proprioceptive loss and healthy individuals [20].

2) Vestibular Input

Age-related changes in vestibular function involve reduced numbers of labyrinthine hair cells, vestibular ganglion cells, nerve fibers and vestibular otolith function [45,46], leading to a reduction in vestibular information received. Vestibular loss or disruption results in increased COM movement in response to perturbation and an alteration in the equilibrium goal (the end goal of upright stance) [47].

Kinematic changes have been noted both with vestibular loss and with vestibular disruption – often achieved by galvanic vestibular stimulation (GVS). Excessive amounts of trunk roll and high trunk pitch velocity is seen in those with vestibular loss [38]. This excessive movement can be destabilizing during a response to perturbation and may be due to high paraspinal activity. GVS alters the equilibrium position – resulting in changes in the movement of the COM late in the response (between 1.5 – 2.5s, well beyond the initial reaction), as well as a different resultant final position [47,48].

Automatic postural response onset in those with vestibular loss is delayed in response to rotational perturbations [38], and the amplitude of the automatic postural response is dampened in leg and trunk muscles [38,49-51]. Importantly, coordination is affected – changes in the pattern of muscle response amplitude vary with the direction of platform rotations, particularly in individuals with bilateral vestibular loss. These individuals exhibit reduced muscle response amplitudes in response to toes-up rotations, and increased amplitudes in response to toes-down rotations (platform rotates anteriorly) when compared to healthy individuals [38].

With respect to voluntary postural responses to perturbations, vestibular loss and disruption primarily affect the amplitude and coordination of muscle activity. For instance, there is an increase in muscle response amplitude dependent on the direction of platform rotation in individuals with bilateral vestibular loss [38]. Coordination – the pattern of muscle activity, particularly in the leg is altered during voluntary responses when vestibular input is disrupted by GVS, because of the changed representation of verticality [52]. These changes contribute to greater instability and frequency of loss of balance in those with bilateral vestibular loss [38].

3) Vision

Visual changes with age include reduced visual acuity and contrast sensitivity [41,53,54]. Vision is an important sensory contributor to postural control and reductions in vision result in altered kinematics and increases in the amplitude of automatic postural responses.

The role of vision on movement kinematics during stepping has been investigated by altering visual input prior to or during the perturbation. When vision is removed at perturbation onset, accuracy of grasping reactions is reduced in healthy individuals; when vision is blocked until perturbation, the timing of grasping reactions is delayed [34]. This suggests that visual changes could have an impact both on timing and accuracy of grasping. However, when vision is simply distracted by a visuo-motor tracking task, participants are still able to avoid obstacles during stepping without redirecting their gaze [55].

The absence of vision does not seem to affect the onset of automatic postural responses as this may be governed by other factors, such as proprioception. Nakata and Yabe [56] found no difference in the onset of muscle response to forward translation perturbation between sighted individuals with eyes open, sighted individuals with eyes closed, and congenitally blind individuals. However, the amplitude of the ankle muscle response is increased during rotational perturbations with eyes closed [19,57] and during upper body perturbations [58]. No difference in the coordination of muscle activity has been noted between eyes closed and open in healthy subjects [19].

The amplitude and coordination of the voluntary response to perturbation is not affected by eye closure [19]. Interestingly however, reaction time – measured by pressing a button, is significantly shorter in congenitally blind individuals than sighted subjects [56]. Visual impairment, a common occurrence in elderly individuals, may have a limited but significant effect on postural control, mainly by increasing the amplitude of automatic postural responses.

4) Muscle strength

There is a significant loss of muscle strength beyond the loss of muscle mass seen with aging. Decreases in isometric and concentric muscle strength have been noted, mostly in cross-sectional studies [59,60]. Isometric strength seems vulnerable to the effects of aging, with one study noting a decline of 1 – 1.5% of maximum voluntary contraction (MVC) per year in ankle plantarflexors and dorsiflexors, starting in the 6th decade [61]. One of the few longitudinal studies to assess muscle strength over 5 years in men and women in their 70s found reductions in concentric quadriceps torque of 16% and 13% over the duration of the study, respectively [62]. The rate of muscle strength decline with age has been shown to be faster than the rate of muscle mass decline [63], and may be due to changes in contraction velocity and intra-muscular connective tissue infiltration. Reductions in specific force – the force per unit of muscle cross-sectional area, have been noted [64]. While isometric and concentric strength have been shown to decline with age, research has highlighted the ability of older adults to maintain eccentric strength. Eccentric quadriceps strength appears to be relatively preserved, declining at a slower rate than isometric or concentric strength [63]. This relative preservation of eccentric strength is supported by evidence that shows longer twitch contraction and half-relaxation times in the elderly [65]. While it is unknown what type of strength may be most important for preventing falls, the level of isometric strength appears to be predictive of faller status [66] and levels of concentric strength are associated with performance on tests of balance [67]. It has also been hypothesized that eccentric strength may be the predominant type of muscle contraction necessary for the recovery of posture after perturbation [68]. Thus, maintenance of eccentric strength could be particularly important for reducing falls risk.

Many physiological changes in muscle composition have been reported that contribute to a reduction in force generation capacity of older adults. Research has shown a decrease in pennation angle of the gastrocnemius muscle [69]. While the pennation angle mechanically affects the capacity to generate force, the reduction in angle has been hypothesized to be due to a reduction in muscle fiber number. There is also an increase in non-contractile tissue and fat infiltration in muscle [70,71], as well as a reduction in both type I and type II muscle fibers [60]. The reduction of type II muscle fibers is compounded by a selective atrophy of type II muscle fibers [60,72]. Muscle weakness has been shown to result in kinematic alterations in postural response to perturbation and increases in automatic and voluntary postural response amplitudes.

Distal muscle weakness, such as in the lower legs, results in an inability to counteract body motion in response to perturbation [73]. This results in large COM movement in response to perturbations in all directions. Those with proximal muscle weakness (such as thigh or trunk muscles) experience greater COM peak velocity than patients with distal weakness (interpreted as instability) when falling backwards, from a toes-up platform rotation [73]. While this highlights the importance of identifying where muscle weakness may be present in individuals at risk of falling, those with distal muscle weakness tend to have much greater strength deficits than those with proximal weakness, limiting the ability to directly compare proximal to distal strength deficits when analyzing postural responses.

Gains in strength and their effect on postural responses to perturbations have also been evaluated in heavy resistance training studies. These studies tend to include 10 – 13 weeks of heavy resistance training that emphasize low volumes and high intensity. In one training intervention, an increase in mediolateral COM displacement in response to a small perturbation (4° over 5 seconds) with eyes closed was seen in the training group after 12 weeks of exercise [74]. These results suggest that the training intervention undertaken had no positive effect on dynamic postural control, as greater COM movement is traditionally considered to mean worse postural control. Alternatively, they may be more willing to allow greater COM movement as a result of the strength training. In a similar training study, an increase in the peak ankle torque as well as the rate of torque production in response to perturbation was seen in one study of 10 weeks of training [75], which is considered a positive effect on dynamic postural control. These conflicting results highlight the need for further research into the effect of strength training on all aspects of postural control.

Automatic postural response onsets do not appear to be affected by muscle weakness, with no difference noted between healthy individuals and those with distal or proximal weakness [73]. The amplitude of the muscle response is increased in response to forward translation perturbations in those with distal muscle weakness, which may be a sign of compensation in response to the muscle weakness [73]. However, following 13 weeks of lower-limb strength training, no differences in the amplitude of lower leg muscular response (of both tibialis anterior and peroneus longus) to perturbation [76] were observed. While the research on muscle weakness and that on strength training is conflicting, there are some factors in studies of heavy resistance training that could contribute to this potentially discordant result. Importantly, training interventions have not included muscles that act primarily in the frontal plane, such as hip abductors and adductors. These muscles have been hypothesized to be important in dynamic postural control, particularly in controlling lateral stability, and are thought to be weakened in older adults [30]. These results also highlight the need to determine whether a minimum strength gain is necessary before improvements in dynamic postural control become apparent. With initial results of the effects of strength training on dynamic postural control being conflicting, more information is needed about postural responses to perturbation after strength training. Also, it is important to note that these training programs emphasized concentric strength; the effect of increases in isometric or eccentric strength is unknown. Eccentric strength may be particularly important for generating force quickly in order to stop unwanted motion, such as after an external perturbation.

Voluntary muscle response amplitude is also affected by muscle weakness. For instance, an increase in paraspinal and hamstring muscle amplitude is noted 500 – 800 ms after forward translation in individuals with proximal muscle weakness, and more so in individuals with distal muscle weakness [73]. This may be part of an effort to regain stability in response to the large COM velocity after perturbation, and is seen as compensation for the instability. Further studies on muscle weakness need to investigate the effect of strength training on the voluntary postural response.

5) Muscle power

Recent studies have investigated the effect of aging on muscle power – the product of force and velocity – and have found considerable deficits. Aging consistently results in a reduction in muscle power [77,78]. Specifically, studies have found a decrease in maximum power [78], and an increase in time to reach peak velocity [79]. At maximum power, both force and velocity decrease with age [77]. Power may be particularly important in the ability to generate effective responses to perturbations quickly, and increases in power appear to reduce centre of pressure (COP) movement in response to perturbation.

To date, only one study has looked at the direct effect of altered muscle power on dynamic postural control. In a randomized controlled trial assessing power training intensity on postural responses to continuous perturbation, low intensity power training (5 exercises including upper and lower body) over 10 weeks significantly increased peak power and reduced COP displacement in response to perturbation [80]. However, it is unknown what the effect of this training was on other facets of dynamic postural control, such as muscular responses to perturbation, and whether the same effects would be observed in response to a transient unpredictable perturbation, as opposed to continuous perturbations.

6) Muscle fatigue

Over the course of any given day, older adults may experience fatigue from daily activities. Muscle fatigue can result in reduced muscle strength and balance, and in young people muscle fatigue has been shown to affect balance and walking patterns [81]. Callahan and Kent-Braun [82] found no influence of age on fatigue effects during sustained voluntary isometric contractions. However, fatigue did result in reduced power at higher velocities [82]. Due to the high movement velocities involved in postural reactions, the reduced power due to fatigue may influence the ability of older adults to respond to perturbations and recover postural control [83], but this hypothesis is disputed in the literature [84]. Fatigue has been shown to alter the movement of the COM after perturbation, reduce the amplitude and delay the onset of the automatic postural response, and alter muscle coordination. While an increased time to decelerate the COM – with greater knee flexion after a forward fall – is noted after submaximal fatiguing contractions (dynamic squats), this did not affect the ability of individuals to recover from the fall, as measured by reaction time and time to touchdown [85]. Fatiguing exercise reduces the amplitude and increases the onset of quadriceps response to postural perturbations [86], however the response of lower leg muscles to the postural perturbations is not known. The coordination of muscle response when fatigued may also be affected. For instance, there is a reduction in co-activation of the hamstrings and quadriceps in response to translational perturbations after fatiguing contractions, with greater reductions in hamstring muscle activity [86]. Fatigue could also exacerbate the effect of other concomitant factors seen with aging (such as reduced muscle strength), further degrading dynamic postural control.

In the following sections, neuromuscular changes associated with aging that may have an effect on dynamic postural control, but have not been directly linked, will be reviewed. The possible effects on dynamic postural control have been previously hypothesized and are included in the discussion of the neuromuscular change.

7) Motor Unit Discharge Rate

A common neuromuscular change associated with aging is a decrease in the motor unit discharge rate, linked with changes in motor unit composition and number. Research has shown a decrease in motor unit number in multiple muscles important in postural control in humans, including the tibialis anterior [87], soleus [88], and biceps brachii [89] with age. The rate of decline of motor neurons in the spinal cord has been estimated at 1% per year beginning in the 3rd decade of life [90]. There is also evidence of motor unit remodeling with age. Fast motor unit axons degenerate, resulting in the denervation of type II muscle fibers [91] and re-innervation by slow motor units. The decrease in the motor unit firing rate is particularly evident at force levels above 50% MVC [92,93]. Roos [94] suggests that a decrease in motor unit firing rate may contribute to age-related decreases in force output. The effect of muscle weakness on kinematics of postural responses and amplitudes of muscle responses has been described above under section *iv* - Muscle Strength.

8) Muscle Contraction Velocity

Aging has also been associated with reduced contraction velocity of muscles. Evidence of this includes decreased sarcoplasmic activity [95] and a decrease in actin sliding speed, observed in the lower limbs [96]. Aging is also linked to selective atrophy of type II muscle fibers [60] – those in their 30s and 40s have type II fiber areas 20% greater than type I. By age 85, type II fiber area is 50% that of type I [72,97]. Muscle contraction velocity is affected by the atrophy of type II fibers, and further dampened by a reduction in muscle fascicle length observed with age [69]. Longer contraction and half relaxation times [65] have been noted in older adults compared to younger controls. Reduced contraction velocity may contribute to reduced muscle power, muscle force and force generation, but it could also negatively affect the maintenance of eccentric strength with aging [94]. Muscle weakness, as detailed above, may alter the postural response to perturbation.

9) Inter-limb Coordination

Reduced inter-limb coordination, or the reduced ability to move two limbs simultaneously, is also associated with age [98]. For example, Fujiyama et al [98] investigated hand and foot coordination during inter-limb movements – older adults demonstrated worse coordination compared to younger controls. Inter-limb coordination is needed for movement execution, such as walking [98]. While there are some key differences between compensatory stepping and volitional movement [30], the majority of falls occur during walking or moving, and elderly individuals have been shown to experience more limb collisions while defending against falls [29]. Thus, the role of inter-limb coordination in dynamic postural control, particularly during stepping reactions may need to be investigated further.

10) Tendon Stiffness

Beyond muscle itself, changes in tendon composition with aging can result in diminished motor performance, including reduced muscle force generation. Decreased tendon stiffness has been found with aging [99]. A reduction in tendon stiffness has been hypothesized to affect the rate of moment generation, as well as the rate of afferent feedback about muscular changes [99]. These changes could increase the time to transmit forces from muscle to bone [100], affecting the ability of the neuromuscular system to respond immediately to unexpected perturbations in the environment.

11) Voluntary Activation Capacity

Finally, while literature on differences in the voluntary activation capacity of young and old adults is equivocal [101], deficits that may contribute to a reduction in central drive have been observed, such as decreased cortical excitability [102]. Reduced voluntary activation capacity via reduced central drive has been hypothesized to compound muscle weakness [94,103]. As described above, muscle weakness has been shown to affect both kinematics and muscle responses to perturbation. However, because of the submaximal levels of force often required for dynamic postural control, it is unclear what role voluntary activation capacity, a factor measured using MVCs, might play in dynamic postural control during most postural perturbations.

Neuromuscular Changes, Postural Control and Knee Osteoarthritis

While aging results in neuromuscular changes, even greater neuromuscular deficits, which may impact dynamic postural control, are seen in musculoskeletal conditions such as knee OA. OA is characterized by a degradation of articular cartilage, sclerosis of subchondral bone, and osteophyte formation on radiographs, with symptoms of joint pain and stiffness [104,105]. OA results in a loss of function and an increase in physical disability, placing a significant toll on quality of life [4]. Research has traditionally focused on the physiological and functional changes in OA, with an emphasis on assessing and treating such deficits.

Previous studies have highlighted the high prevalence of falls in samples of individuals with OA – over 50% [8-10], although not all of these studies were limited to those with OA. Those with knee OA are at a higher risk of falls than healthy elderly individuals, as measured by the Physiological Profile Assessment, a battery of objective tests of falls risk factors [8,11]. These individuals often exhibit many factors that increase the risk of falling, including pain [106], muscle weakness [107], and impaired proprioception [108]. Compounding this is a greater fear of falls in individuals with knee OA compared to age-matched healthy controls [8].

To date, there are no studies that evaluate dynamic postural control in knee OA. Studies of static postural control have highlighted many deficits in those with knee OA compared to healthy age-matched controls, mainly in relation to postural sway (quantified by variation in the COP) and COM displacement [109-114]. When examining balance during gait, those with OA have also been shown to have a greater propensity to trip on an obstacle [115]. Given the deficits in static postural control and gait, it can be hypothesized that those with knee OA may also exhibit disordered or inadequate postural responses to perturbations; however this has not been examined. It has also been noted that postural control deficits and factors that increase the risk of falls in knee OA, such as muscle weakness, may be amenable to change. For instance, increasing muscle strength via aquatic exercise [116] and Tai Chi [117] improved falls efficacy and reduced the fear of falling in individuals with knee OA. Other studies have shown improvements in static postural control with increased muscle strength [10]. These results are promising and suggest that some neuromuscular deficits that may exist in knee OA, resulting in dynamic postural control difficulties, may also be amenable to training.

In order to develop effective balance treatment and fall prevention strategies for those with knee OA, it is important to understand the role of neuromuscular deficits beyond normal aging that are attributed to the disease, and evidence supporting their role in dynamic postural control. Neuromuscular changes above and beyond normal aging include pain, reduced joint proprioception, muscle weakness and reduced muscle power. Those with OA may also experience reduced motor unit firing rates and reductions in voluntary activation capacity. An understanding of such factors and their effect on dynamic postural control in individuals with knee OA could be critical in successful fall prevention and treatment strategies.

Joint pain is a central characteristic of OA, and is part of the American College of Rheumatology criteria for the clinical diagnosis of knee OA [118]. Joint pain alters the kinematics and kinetics of postural responses, and affects the coordination of muscle activity during automatic postural responses. Experimentally-induced pain in healthy young individuals results in significant kinematic changes to the postural response during perturbation. Experimentally-induced knee pain in healthy individuals results in shifts in the COP during forward perturbation [119], while experimentally-induced thigh pain results in increased time to return to equilibrium after perturbation [120]. Trunk torque is reduced in response to a rotational perturbation in individuals with low back pain compared to healthy controls [121]. The coordination of trunk muscle activation is also affected by low back pain in response to perturbation [122]. Though it is clear that pain has a significant effect on the kinematic and kinetic response to perturbation, further investigation into the role of pain, and particularly joint pain, is needed to better understand the effects of pain on all aspects of dynamic postural control – including automatic and voluntary postural responses to perturbations.

Those with knee OA have greater difficulty with joint repositioning tests [110,123], a measure of joint proprioception, than healthy age-matched controls. For instance, those with knee OA were successful in only 7.5% of joint repositioning trials, as compared to 53% on target for age-matched healthy individuals [123]. Those with OA also have a much higher threshold for sensing joint movement [124] meaning a greater amount of movement occurs before it is detected. This lowered sensitivity to movement could result in a longer time to perceive, and recover from, postural perturbations. Disruptions to joint proprioception, as seen in individuals with lower leg and total leg proprioceptive loss, result in altered kinematics and kinetic responses to perturbation, as well as delayed onset and dampened muscle amplitude of automatic postural responses, as described above. However, proximal proprioception loss, such as of the hip and trunk, may be particularly important in altering postural control responses. In those with knee OA, proximal proprioception has not been assessed. The magnitude of such proprioceptive deficit, if any, and the resultant effect on dynamic postural control is therefore unknown.

Numerous studies have highlighted deficits in isometric and concentric quadriceps [125-127] and hip muscle [128] strength in those with knee OA compared to age-matched controls. This is compounded by a reduction in specific strength as measured in the quadriceps, compared to age-matched controls [127]. When eccentric muscle strength was measured in those with and without knee OA, significant differences were seen. OA patients produced 76% less quadriceps eccentric force than healthy age-matched controls, and this discrepancy is 20% greater than the deficit seen with concentric strength [123]. Muscle weakness is associated with kinematic alterations in the response to perturbation and increases in muscle response amplitude (thought to be compensatory in nature), important factors in maintaining postural control.

Maximal isotonic power of the quadriceps also appears to be reduced in those with OA, particularly those with greater functional disability [129] and higher grades of OA [130]. While the results of one study were compared to population values of muscle power, showing large deficits in leg power for those with knee OA, [130], the studies of muscle power in OA did not include a control group, and thus this comparison to age-matched healthy controls has not been made directly. While the effect of decreased power generation on dynamic postural control has not been investigated, increases in power may alter the kinematics of the response to the perturbation. However, given the few studies of muscle power and dynamic postural control, more research into the role of this neuromuscular factor in defending against falls is needed.

Other neuromuscular changes that may have an effect on dynamic postural control have also been noted. For instance, a reduction in motor unit firing rate in those with knee OA may also exist, however results are conflicting. A small but significant reduction in motor unit firing rate was seen in one study of motor unit properties in the vastus medialis of individuals with OA compared to age-matched controls [131], however this difference was not observed in another study of the same muscle and contraction intensity [126]. Differences could be due to the different techniques used to identify motor units. Importantly, to the author's knowledge, these are the only two studies to date to have been published on motor unit characteristics in knee OA, and thus firm conclusions about motor unit changes with disease cannot be drawn. The possible effect of reduced motor unit discharge rate on postural control, via reduced muscle force generation, has been hypothesized by others [94].

Fortunately, knee OA does not appear to affect limb coordination. When compared to age-matched controls, those with knee OA did not display greater difficulty with limb coordination during walking, as measured by correlation of continuous relative phase curves of the leading and trailing limbs [132]. While interlimb coordination may be reduced with age, possibly affecting stepping reactions, those with knee OA appear to be spared any further deficits.

Finally, results are equivocal about whether voluntary activation capacity deficits exist [110] or not [125] when comparing those with symptomatic knee OA to age-matched healthy individuals. Hassan et al [110] found a reduced percentage of quadriceps activation among those with knee OA, while Lewek et al [125] found no significant difference in quadriceps activation (though nearly 50% of those with OA failed to fully activate their quadriceps). More research is needed to clarify whether subgroups in the population of individuals with OA may differ, such as those with different intensities of pain. Since deficits in voluntary activation may affect maximal muscle force generation, which is linked to alterations in dynamic postural control (though its role in submaximal force generation is unclear), voluntary activation deficits in those with knee OA should be clarified.

Summary

Aging alone is associated with significant changes in dynamic postural control, a key factor in the risk of falling. Differences between young and old individuals have been noted in the kinematics and kinetics of postural responses, as well as the onset, amplitude, and coordination of automatic and voluntary postural responses. Both feet-in-place and change-in-support reactions are affected with age.

Neuromuscular changes are associated with aging, and have been directly linked to alterations in dynamic postural control. These include deficits in proprioception, vestibular and visual changes, muscular weakness, reduced power and fatigue. Other neuromuscular changes have been hypothesized to play a role in dynamic postural control, including reduced motor unit discharge rate, contraction velocity, interlimb coordination, tendon stiffness and voluntary activation capacity. Research linking changes in neuromuscular control with age to impairments in automatic and voluntary postural responses to external perturbations was reviewed. To date, postural control research has highlighted the role of sensory changes such as reduced proprioception, vestibular information and vision in dynamic postural control, as well as the effects of muscle weakness. However, gaps in the literature remain.

Research has highlighted the importance of eccentric strength in the elderly: eccentric strength appears to be more resistant to the effects of aging and may be critical in recovering from postural perturbations by generating force rapidly. Muscular power is being investigated, as it may be functionally relevant to navigating the environment and to recovering from postural perturbations. However, little work has been done to examine the role of these two constructs in dynamic postural control and how altering these, through strength or power training, may improve responses to postural perturbations. Further research needs to examine the role of neuromuscular changes on aspects of dynamic postural control, particularly those that may be amenable to training or rehabilitation in the elderly.

Deficits in dynamic postural control resulting from altered neuromuscular processes observed with ageing are compounded further in older adults with musculoskeletal pathology such as knee OA. Those with knee OA exhibit neuromuscular changes beyond that seen with aging, and evidence suggests that the risk, and rate, of falling is greater in this population. Neuromuscular changes seen in knee OA that negatively impact postural control include joint pain, reduced proprioception, muscle weakness and reduced power. Those with knee OA may also exhibit alterations in motor unit firing characteristics and a reduced voluntary activation capacity. However, few studies have investigated the effect of knee OA on dynamic postural control and the role of these neuromuscular changes, and thus it is not known what changes may particularly influence responses to postural perturbations and ultimately the ability to defend against a fall. Future research needs to evaluate the effect of these changes on dynamic postural control, in order to better understand how those with knee OA respond to, and recover from, unexpected perturbations. Such an understanding is critical to the successful creation and implementation of fall prevention and treatment programs in this patient population.

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