

WJO 5th Anniversary Special Issues (5): Knee**Muscle force and movement variability before and after total knee arthroplasty: A review**

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Author contributions: Smith JW contributed significantly to the intellectual content, review of the literature, and overall organization of the manuscript, as well as wrote the majority of the manuscript; Christensen JC contributed significantly to the intellectual content, review of the literature, and overall organization of the manuscript, and assisted in the writing of the manuscript; Marcus RL and LaStayo PC contributed to the intellectual content and interpretation of data.

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Received: December 29, 2013 Revised: February 26, 2014

Accepted: March 11, 2014

Published online: April 18, 2014

Abstract

Variability in muscle force output and movement variability are important aspects of identifying individuals with mobility deficits, central nervous system impairments, and future risk of falling. This has been investigated in elderly healthy and impaired adults, as well as in adults with osteoarthritis (OA), but the question of whether the same correlations also apply to those who have undergone a surgical intervention such as total knee arthroplasty (TKA) is still being investigated. While there is a growing body of literature identifying potential rehabilitation targets for individuals who have undergone TKA, it is important to first understand the underlying post-operative impairments to more efficiently target functional deficits that may lead to improved

long-term outcomes. The purpose of this article is to review the potential role of muscle force output and movement variability in TKA recipients. The narrative review relies on existing literature in elderly healthy and impaired individuals, as well as in those with OA before and following TKA. The variables that may predict long-term functional abilities and deficits are discussed in the context of existing literature in healthy older adults and older adults with OA and following TKA, as well as the role future research in this field may play in providing evidence-based data for improved rehabilitation targets.

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Key words: Osteoarthritis; Elderly; Total knee arthroplasty; Movement variability

Core tip: Muscle force output and movement variability are important aspects of identifying individuals with mobility deficits, central nervous system impairments, as well as future risk of falling. These correlations have primarily been investigated in elderly healthy and impaired adults, as well as in adults with osteoarthritis (OA), but the question of whether the same correlations also apply to those who have undergone a surgical intervention such as total knee arthroplasty (TKA) are still being investigated. The variables that may predict long-term functional abilities and deficits are discussed in the context of existing literature in healthy older adults and older adults with OA and following TKA.

Smith JW, Christensen JC, Marcus RL, LaStayo PC. Muscle force and movement variability before and after total knee arthroplasty: A review. *World J Orthop* 2014; 5(2): 69-79 Available from: URL: <http://www.wjgnet.com/2218-5836/full/v5/i2/69.htm> DOI: <http://dx.doi.org/10.5312/wjo.v5.i2.69>

INTRODUCTION

Knee osteoarthritis (OA) is the most common type of arthritis, affecting over 37% of Americans 60 years and older^[1]. Of these, approximately 12% have symptoms^[1] that frequently include pain and loss of motion, resulting in restricted activity, decreased neuromuscular control, impaired proprioceptive acuity, and loss of independence during activities of daily living^[2,3]. When symptoms become severe as in late stages of OA, many individuals seek additional treatment interventions that often include the total knee arthroplasty (TKA) surgical procedure. Not surprisingly, the increasing prevalence of knee OA coincides with a growing demand for TKA procedures, with an expected 6-fold increase in surgeries by the year 2030^[4]. In light of this heightened demand, the need for evidence-based rehabilitation protocols that maximize long-term physical and muscle function is critically important.

TKA is often effective for pain relief, but the outcomes of this surgical procedure do not often achieve similar, long-term improvements in both physical and muscle function^[5-7]. To counteract these deficits, it is important to better understand how TKA may influence various physical and muscle performance parameters that predispose an individual to impaired function post-operatively. Muscle atrophy, muscle weakness, and neuromuscular activation deficits are all factors associated with functional impairments in adults with OA and there is a growing body of evidence suggesting that impairments in these areas lead to variability in muscle force output and movement patterns both pre- and post-operatively. The implications of muscle force output and movement variability in the ability to perform functional tasks is underappreciated in the literature, but could hold value in understanding the ramifications of functional impairments, as well as developing focused rehabilitation protocols that improve long-term functional outcomes in the OA and TKA patient populations.

The purpose of this narrative review is to expose and summarize the current evidence related to variability in muscle force output and movement patterns that occur in older individuals with knee OA before and after TKA. The implications of variable muscle force output and movement during common mobility tasks will be highlighted. Further, the concept that variability may have advantages and disadvantages in individuals with knee OA and following TKA will be explored.

For the purposes of this review, variability is described in two contexts: (1) as the variability an individual displays in muscle force output measured by the amplitude of force fluctuations; and (2) as the intra-subject variability during mobility tasks such as level walking. The former includes tasks involving an isolated muscle group, such as the quadriceps, and the latter includes synergistic activities that involve coordinated involvement of several muscle groups such as required during level walking and stair stepping. More specifically, variability in muscle force output is measured as the force fluctuations relative

to a given submaximal force target while performing a specific task. This concept applies not only to measures of muscle function, such as during isolated tasks that aim to evaluate fluctuations of motor output, but to functional tasks such as gait and stair stepping that aim to evaluate fluctuations of temporal, spatial, and kinematic outcomes. For instance, variability during level walking is a measure of the fluctuation in gait characteristics from one step or stride to the next, while variability in negotiating stairs can be witnessed when stepping from one step to the next. These concepts of variability are applicable to both muscle and physical function, as there are studies that have investigated measures of purely muscle force output variability, and others that have investigated movement variability. The one common theme, however, is that both types of investigations have aimed to identify links between the respective measures of variability and the ability to perform functional tasks efficiently^[8-11]. Heretofore, the implications of greater or reduced variability relative to healthy controls, in older adults with OA before and after TKA, have not been previously reviewed.

The initial review of the literature for this narrative review involved a general internet search, as well as a search of PubMed (<http://www.ncbi.nlm.nih.gov/pubmed/>) using several search terms. The initial search was performed to identify the breadth of information regarding variability of motor output, as well as during various movement tasks. Following this review, a more focused search strategy was used that included several keywords (*e.g.*, motor output, gait variability, muscle function, muscle force steadiness, arthrogenic muscle inhibition, stair stepping, TKA, and OA), which were applied to the CINAHL and MEDLINE databases. No specific filtering strategy was used for the types of article, although limits were used to include research in humans only, the English language, as well as dates between 1990 and 2013. Of the articles returned, related articles were also reviewed for relevancy, resulting in a review of articles published prior to 1990.

MUSCLE FORCE OUTPUT VARIABILITY

Diminished quadriceps strength in knee OA and following TKA is coupled to the ability to perform functional tasks that require adequate muscle strength and motor control to perform accurately and within a specified trajectory^[12-14]. Neuromuscular activation deficits accompanied by declines in proprioception^[15] and kinesthetic awareness are common manifestations of knee OA, and contribute to these strength deficits, as well as slower movement patterns^[16-18] and reduced force steadiness^[19-21] before and after TKA^[7,14,18]. These adaptations result in diminished ability to exert a steady force output during submaximal efforts, such as those that are required during activities of daily living, as well as greater variability in movement patterns^[14,20,22]. The importance of understanding how these impairments are altered following TKA is relevant to identifying variables that may be ben-

eficial targets of post-operative rehabilitation.

Arthrogenic muscle inhibition

A significant component of impaired muscle function is the presence of arthrogenic muscle inhibition (AMI), or the inability to fully activate the quadriceps muscle^[23]. Quadriceps AMI is associated with changes in the discharge of afferent, articular sensory receptors resulting from swelling, inflammation, joint laxity, and damage to knee joint afferents, all of which are common symptoms of OA^[24]. Swelling, in particular, has been shown to independently alter joint afferent discharge by increasing the firing frequency and recruitment of group II afferents^[25-27]. Not surprisingly, in the presence of swelling, the greatest muscle inhibition occurs at the extremes of motion, where intra-articular pressure and afferent discharge are the highest^[28-34]. In turn, these changes in neuromuscular control are implicated in the ability to control motor output.

Inflammatory responses and joint laxity also contribute to quadriceps AMI by increasing joint afferent discharge; inflammation *via* sensitization of free nerve endings innervated by group III and IV afferents^[35-37], and joint laxity *via* increases in the activation of mechanoreceptors and nociceptors^[24,38]. While nociceptive influences have some correlation to AMI, the relationship between AMI and pain is inconsistent^[24] in patients with OA^[39] as well as following TKA^[40,41]. Indeed, research suggests that while the presence of pain may accompany AMI, inhibition occurs in the absence of pain as well^[24,34]. Although this research has been useful in clarifying the role of nociceptive influences on AMI, the overall effects on muscle force output variability, as well as movement variability during specific functional tasks have not been identified.

In addition to the increases to joint afferent discharge discussed thus far, as described by Rice *et al*^[24] these disruptions may be accompanied by simultaneous decreases in afferent output due to damage to articular receptors^[38,42-44] and subsequent effects on reflex pathways within the spinal cord. The potential contributors to these reflex pathway adaptations include group I non-reciprocal (Ib) inhibitors^[45], interneurons associated with the flexion reflex^[46-48], and dysfunction of the gamma (γ)-loop^[24], with the overall effect being inhibition of the quadriceps α -motoneuron pool^[38,43,44,49]. Research suggests that all of these pathways contribute to AMI, with the relative contributions dependent on factors such as the extent and location of joint damage, swelling, inflammation, and laxity^[24,34].

In individuals with OA, the different neural mechanisms described above involve a series of complex innervation strategies that contribute to quadriceps AMI, motor output variability, and associated force control. Total knee arthroplasty, by nature, results in disruption of the joint capsule and ligamentous structures [either anterior cruciate ligament (ACL) or ACL and posterior cruciate ligament (PCL)], as well as alterations to joint motion and as a result, would be expected to influence mechanisms

that contribute to AMI that rely specifically on afferent discharge from these structures. Although TKA has been shown to reverse some of the pre-operative impairments by improving proprioception and joint stability, similar improvements in muscle and mobility deficits following TKA persist. The significance of these neuromuscular changes in individuals that undergo TKA is not well understood. That is, the factors that influence the extent to which these changes affect muscle force output variability and movement variability following TKA have not been thoroughly investigated^[34].

Muscle force steadiness

Lower extremity muscle force steadiness (MFS) has been identified as a potential marker of impairment during functional tasks such as walking endurance, chair rising and stair climbing^[13]. Moreover, correlations between concentric and eccentric quadriceps force steadiness and aging, as well as between eccentric steadiness and falling in elderly adults have been reported^[50]. Although these studies were not performed in subjects with OA, they provide a basis for understanding the relationship between force steadiness and functional abilities, and subsequently, insight into how they may be altered by deficits common in OA. A summary of research that has focused specifically on lower extremity motor output variability, also reported as force steadiness, in elderly adults, and in OA before and after TKA is included in Table 1.

In elderly adults, the ability to control lower extremity submaximal muscle forces has been shown to be an independent risk factor for increased risk of falling^[13,50]. Carville *et al*^[50] compared force steadiness between young and older adults and found that the younger, non-fallers were steadier than older fallers, with eccentric contractions showing the strongest correlation with falling. This finding was consistent with another study that showed that the CV of force steadiness for both isometric and anisometric (*i.e.*, concentric and eccentric) force output was greater in older adults compared to young adults^[58]. Hortobágyi *et al*^[52], however, showed increased muscle force variability in older adults during concentric and eccentric contractions, but not in isometric contractions. Furthermore, Tracy *et al*^[22] showed a reduction in MFS during isometric, but not concentric and eccentric contractions in healthy older adults compared to young adults. The differences in these findings may be due to inconsistencies in the speed of contraction, as well as in the proportion of the target force relative to the subjects' MVIC. While these discrepancies may appear relatively minor, it is evident that they can have large consequences on the efficiency and control of motor output^[13,53]. As an example, Seynnes *et al*^[13] reported isometric steadiness was an independent predictor of chair-rise time and stair-climbing power, while Manini *et al*^[53] demonstrated no correlation between isometric force steadiness and functional tasks including chair-rise time or time to ascend and descend stairs in older adults. The differences in these studies persist regardless of the fact that both employed an isometric force-matching task at 50% of

Table 1 Summary of the literature addressing muscle force output variability in older adults and those with osteoarthritis before and after total knee arthroplasty

Study	Population	Purpose/hypothesis	Variables assessed	Significant findings
Older adults with native, non-arthritis knees Carville <i>et al.</i> ^[60] , 2007	n = 44 (Young adults; Age range = 18-4 yr) n = 78 (Older adults; Age range > 70 yr) n = 24 (Young, active adults; Mean age = 25.3 yr) n = 24 (Older active adults; Mean age = 73.3 yr)	To investigate isometric and anisometric quadriceps contractions in healthy young and older adults	Muscle strength; CV of isometric force steadiness at 10%, 25%, and 50% of MVC; and SD of acceleration of anisometric steadiness during concentric and eccentric contractions against two external loads of 1 and 5 kg Muscle strength; Isometric force steadiness at 90 degrees of knee flexion; and Concentric and eccentric force steadiness at 25 deg/s	1. Non-significant trend for younger subjects to be most steady and fallers least study 2. Isometric force steadiness was unaffected by the level of force output. 3. Fallers were less steady than both young and non-fallers 4. Older adults were less steady during eccentric contractions than the younger adults and fallers were the least steady 1. CV of force steadiness for all contractions was greater in older subjects than younger subjects 2. Muscle strength was similar for all three types of contractions Younger subjects were stronger than older subjects
Christou <i>et al.</i> ^[51] , 2002	n = 27 (Older adults; Mean age = 72 yr) n = 10 (Young adults; Mean age = 21 yr)	To examine the ability to control knee-extension force during discrete isometric, concentric, and eccentric contractions	Muscle strength Quadriceps force accuracy and steadiness during isometric, concentric and eccentric contractions performed at 25 N target force	1. Older subjects had significantly more force variability (<i>i.e.</i> , were less steady) during eccentric and concentric, but not isometric contractions 2. Force variability and accuracy were correlated with each other, but not with maximal strength 3. Training significantly improved force accuracy and variability during eccentric and concentric contractions Isometric quadriceps force steadiness was not a predictor of functional performance in older subjects
Hortobagyi <i>et al.</i> ^[53] , 2001	n = 50 (Healthy, older adults; Mean age = 76.2 yr)	To compare the effects of low- and high-intensity strength training on maximal and explosive strength and on the accuracy and steadiness of submaximal quadriceps force in elderly humans	Isometric knee extensor steadiness at 50% MVC; Chair rise time Time to ascend and descend stairs; and Walking velocity	1. Isokinetic submaximal force control was equally diminished in both young and older adults compared to isometric force control 2. As the force level increased, force variability decreased for both young and older adults
Manini <i>et al.</i> ^[53] , 2005	n = 19 (Healthy older adults; Mean age = 71.8 yr) n = 20 (Healthy young adults; Mean age = 25.8 yr)	To determine how knee extensor steadiness during an isometric task is related to performing four everyday tasks that included chair rising, walking at a fast pace, and stair ascending and descending	Isokinetic force variability at two different force levels; 20% of MVC and 60% of MVC	1. Steadiness of old adults was reduced compared with young adults during isometric, but not during concentric and eccentric contractions 2. Decline in steadiness was not associated with differences in EMG magnitude
Schiffman <i>et al.</i> ^[54] , 2001	n = 10 (Healthy young adults; Mean age = 22 yr) n = 10 (Healthy older adults; Mean age = 72 yr)	To compare the steadiness and EMG activity of young and old adults while they were performing submaximal isometric and anisometric contractions with the knee extensor muscles	Muscle strength; EMG of quadriceps muscles during experimental tasks; and Isometric, concentric, and eccentric force steadiness for 10-12 s at 2%, 5%, 10%, and 50% of MVC	1. Force fluctuations during submaximal isometric contractions did not change with training 2. Force fluctuations during submaximal anisometric contractions with a 50% load declined for both heavy and light training groups
Tracy <i>et al.</i> ^[52] , 2002	n = 26 (Healthy, older adults; Mean age = 77.7 yr)	To determine the effect of strength and steadiness training with heavy loads by old adults on the fluctuations in force and position during voluntary contractions with the quadriceps femoris muscles	Muscle strength (MVC); Force fluctuations during isometric contractions at 2%, 5%, 10%, and 50% of MVC; Force fluctuations during concentric and eccentric contractions at 5%, 10%, and 50% of MVC; EMG activity of the quadriceps muscles during	

Seymes <i>et al.</i> ^[3] , 2005	<i>n</i> = 19 (Healthy older women; Mean age = 77.9 yr)	To assess the relationship between knee-extensor force-control capacity, as MVC measured by isometric force steadiness and accuracy, and functional limitations in healthy older adults	experimental tasks; and Physical function tasks including gait speed, chair rise, and stair ascent and descent	1. Isometric steadiness independently predicts chair-rise time and stair-climbing power 2. None of the accuracy measures were significantly associated with any of the functional performance tests
Older adults with osteoarthritic knees Hortobágyi <i>et al.</i> ^[56] , 2004	<i>n</i> = 20 (Older adults with OA; Mean age = 57.5 yr)	To characterize the distribution of error Quadriceps force accuracy and steadiness during 1. Knee OA subjects needed 67% more time to complete functional tasks, in knee joint proprioception, quadriceps a force target-tracking task during anisometric produced 82% more proprioception errors, and 89% more errors in force accuracy and steadiness and muscle contractions.	Functional performance measures including walking endurance, chair rising, and stair climbing	Walking endurance was related to muscle strength, but not steadiness
Sorensen <i>et al.</i> ^[57] , 2011	<i>n</i> = 20 (Controls; Mean age = 56.8 yr)	To investigate the relationship between Submaximal isometric quadriceps force steadiness Quadriceps force steadiness does not predict peak knee adduction moment	Functional performance measures including walking endurance, chair rising, and stair climbing	2. Knee OA subjects had 155% more force variability, with eccentric contractions being particularly unsteady
Older adults following total knee arthroplasty Smith <i>et al.</i> ^[64] , 2013	<i>n</i> = 41 (Older adults with OA; Mean age = 62 yr)	To compare muscle force steadiness of quadriceps force output in individuals with knee OA before and after TKA, and to a group of age-matched controls with native knees	Submaximal isometric quadriceps force steadiness during ambulation	Quadriceps force steadiness was significantly lower in the OA group relative to controls
	<i>n</i> = 13 (Older adults with TKA; Mean age = 62.7 yr)			1. Pre-operatively, quadriceps force steadiness for both concentric and eccentric contractions was significantly higher in the OA group relative to controls; and
	<i>n</i> = 11 (Controls; Mean age = 62.2 yr)			2. Post-operatively quadriceps force steadiness for both concentric and eccentric contractions was significantly lower in the OA group relative to controls
				Muscle strength was significantly lower in the TKA group both pre- and post-operatively compared to controls

CV: Coefficient of variation; MVC: Maximal voluntary contraction; OA: Osteoarthritis; TKA: Total knee arthroplasty; EMG: Electromyographic signal.

MVIC. These discrepant findings underscore the need for further research to identify the associations between the ability to control submaximal muscle forces and specific functional tasks in order to identify specific rehabilitation targets.

To shed more light on potential relationships between force steadiness and functional performance, Hortobágyi *et al.*^[56] investigated lower extremity steadiness during submaximal isometric and anisometric contractions and showed that knee OA was associated with 155% more force variability and 67% more time to complete functional tasks than a group of age- and sex-matched controls without OA. In contrast, Sorensen *et al.*^[57] identified no relationship between quadriceps force steadiness and peak knee adduction moment during level walking in subjects with knee OA, suggesting that submaximal isometric MFS and knee joint loads during walking represent two distinctive pathways with independent influences on knee OA pathogenesis. These studies lend support for potential relationships between the ability to control submaximal muscle forces and functional tasks in individuals with OA, but the specific correlations remain to be clarified. Consequently, it must also be considered that MFS may represent a distinctive pathway that does not have broader applicability to functional tasks.

Thus far, MFS in both older adults and those with knee OA have been discussed and while the methodologies, level of force exerted, and type of contractions vary between studies, there appears to be an overall trend that some aspect of force steadiness is worse in both elderly individuals and those with OA compared to healthy young and age-matched controls. In this regard, Enoka *et al.*^[42] described mechanisms that may contribute to the amplitude of force fluctuations between young and old adults as being primar-

ily dependent on the behavior of motor units; namely, the motor unit force and discharge rate variability.

Total knee arthroplasty, by nature, involves the removal of damaged structures and has been reported to positively affect proprioceptive feedback in individuals with OA^[14,59,60]. Additionally, evidence suggests that following TKA, - which type of prosthesis - PCL retaining or PCL sacrificing? How long after surgery? what was the rehabilitation program after surgery regarding physio? there is a significant improvement in MFS to a level that exceeds a group of healthy, age-matched controls without OA^[14]. In this study, subjects were examined within one month prior to surgery and at 6-mo post-operatively and were not stratified by ligament retention status or type and extent of post-operative rehabilitation. The authors of this study showed that while quadriceps force steadiness was significantly worse before TKA compared to an age-matched, symptom-free group of controls, following TKA, steadiness improved to a level that exceeded healthy controls^[14]. These results raise an important question about motor output variability, *i.e.*, is there a level of steadiness that is too low and corresponds to impaired, rather than improved movement ability, and that may have implications for functional tasks? Certainly, a better understanding of how these changes in force control and steadiness following TKA correlate with other functional performance parameters could direct the development of future intervention strategies and improve long-term TKA outcomes.

MOVEMENT VARIABILITY

Similar to MFS, greater movement variability in elderly individuals as well as in those suffering from OA, is generally considered representative of a pathological or impaired state and has been associated with reduced function and future risk of mobility deficits^[61,62]. For example, Brach *et al.*^[62] used stance time variability (STV) during level walking to identify an optimal level of gait variability, above which was an indicator of prevalent mobility disability. And although these findings are well-correlated in the literature, the implications of reduced variability relative to healthy, age-matched controls have received little attention. The next section aims to explore the implications of both increased and decreased movement variability in those with OA before and after TKA. To assist in this review, Table 2 presents an overview of the current literature regarding movement variability during level walking in these patient populations.

Level walking variability

Gait is a multifaceted and complex task that requires coordinated movement between both central and peripheral neuromuscular control mechanisms. And while variability during gait has been shown to be associated with incident fall risk in elderly adults^[66], and predict mobility deficits in different populations^[62,66]_ENREF_62, there are conflicting reports on which variables are associated with

these functional parameters. These inconsistencies only serve to propagate the lack of consistent and effective rehabilitation protocols for both individuals with knee OA as well as following TKA.

Muscle function and proprioceptive deficits associated with knee OA have been suggested to contribute to altered, spatio-temporal, kinematic, and kinetic gait patterns compared to individuals without OA^[61,71-75]. The resulting gait pattern is characterized by slower gait speed and cadence, reduced stride length, and altered movement patterns that are particularly evident during the loading phase of the gait cycle^[61,73,75]. However, since OA represents an increased level of pathology with associated neuromuscular changes beyond those that may be associated with aging alone, it is important to first clarify the changes in movement variability that may occur in older adults without OA.

Researchers have investigated several measures of gait variability in older adults to identify meaningful changes that may be associated with disability or impairment, which included the standard deviations (SD) of step width, stance time, swing time, and step length^[61,63]. The results showed that increased STV is a predictor of central nervous system impairments^[61] and mobility disability in elderly community-dwelling adults^[62,64]. In a similar study, variability of gait was assessed in 100 frail community-dwelling adults by using velocity and cadence, as well as the CV of stride time, step width, double support time, and stride length as the predictor variables. The authors found that regulation of gait was impaired in older adults and that frailty was associated with higher variability of all gait parameters^[76]. Callisaya *et al.*^[66] also investigated gait variability in older adults, but with the purpose of correlating gait measures with risk of falling. The authors assessed the relationship between the SD of velocity, cadence, step length, step width, step time, and double support phase with incident fall risk and found non-linear associations between velocity, cadence, and step time variability with multiple falls, although, none of the variables predicted risk of single falls^[66].

The breadth of literature regarding gait variability in older adults is largely consistent across studies; *i.e.*, greater variability equates to greater impairment, and based on the known deficits that accompany OA, these findings would be expected to be consistent in individuals with OA. In fact, gait variability has been correlated with severity of OA^[9,71]_ENREF_75, as well as risk of future falls and gait instability before and after TKA^[11,69,72,77]. As an example, Lewek *et al.*^[10] investigated 15 subjects with unilateral OA and 15 age and gender-matched controls to quantify frontal plane, knee motion variability, which was assessed by the phase angle (knee angle *vs* angular velocity) during early stance phase of level walking. The authors found that despite altered involved side knee kinematics and kinetics, there were no differences between frontal plane variability between the two groups. In fact, the variability in the involved limb was significantly lower than the variability of the uninvolved knee's mo-

Table 2 Summary of the literature addressing gait variability in older adults and those with osteoarthritis before and after total knee arthroplasty

Study	Population	Purpose/hypothesis	Variables assessed	Significant findings
Older adults with native, non-arthritic knees Brach <i>et al.</i> ^[61] , 2012	n = 552 (Older adults; Mean age = 79.4 yr)	1. Determine the magnitude of STV that discriminates individuals who currently have mobility disability. Determine the magnitude of STV that predicts a new onset of mobility disability at 1 yr	Gait Variability: Stance time variability Self-reported walking disability	1. Values of STV may be useful in recognizing mobility disability and future disability 2. Recommend using 0.034 s as the cutoff
Brach <i>et al.</i> ^[61] , 2010	n = 241 (Older adults; Mean age = 80.3 yr)	1. To estimate clinically meaningful change in gait variability over time. Greater gait variability is a predictor of future falls and mobility disability	Gait Variability: Step width, Stance time, Swing time, Step length	Preliminary criteria for meaningful change are 0.01 s for stance time and swing time variability, and 0.25 cm for step length variability
Brach <i>et al.</i> ^[61] , 2008	n = 558 (Older adults; Mean age = 79.4 yr)	1. CNS impairments will affect motor control and be manifested as increased stance time and step length variability. Sensory impairments would affect balance and manifest as increased step width variability To determine if gait variability adds to the prediction of incident mobility disability independent of gait speed	Gait Variability: Step width, Stance time, Step length, Strength Measures: Grip strength, Repeated chair stands	CNS impairments affected stance time variability especially in slow walkers, while sensory impairments affected step width variability in fast walkers
Brach <i>et al.</i> ^[61] , 2007	n = 379 (Older adults; Mean age = 79 yr)	To determine if gait variability adds to the prediction of incident mobility disability independent of gait speed	Gait speed, Step length, Stance time, STV	1. After adjusting for gait speed and other comorbidities, only stance time variability remained an important indicator of disability 2. STV of 0.01 s was associated with a 13% higher incidence of mobility disability
Brach <i>et al.</i> ^[61] , 2005	n = 503 (Older adults; Mean age = 79 yr)	To examine the linear and nonlinear associations between gait variability and fall history in older persons and to examine the influence of gait speed	CV of step width, CV of step length, CV of step time, CV of stance time, Gait speed, Fall history	1. Step width variability had the highest correlation with fall history, which only existed in subjects that walked > 1.0 m/s 2. Step length, stance time, and step time variability were not associated with fall history
Callisaya <i>et al.</i> ^[61] , 2011	n = 411 [Older adults; Mean age = 72.6 yr (lost to follow-up); 71.2 yr (no falls); 72.3 yr (single fall); 73.9 yr (multiple falls)]	To investigate the associates of gait and gait variability measures with incident fall risk	Gait Variability: Step length, Step width, DSP, Gait speed, Cadence, Step time	Associations with multiple falls were present for gait speed, cadence and step time variability
Maaki <i>et al.</i> ^[67] , 1997	n = 75 (Older adults; Mean age = 82 yr)	To determine whether specific gait measures can predict the likelihood of experiencing future falls or whether they are more likely to be indicative of adaptations associated with pre-existing fear of falling	Gait Variability: Stride length, Stride width, Stride period, Double-support, Stride velocity	1. Stride-to-stride variability in gait is a predictor of falling 2. Wider stride does not increase stability but does predict an increased likelihood of experiencing falls
Older adults with osteoarthritic knees Lewek <i>et al.</i> ^[60] , 2006	n = 15 (Older adults with OA; Mean age = 48.7 yr); n = 15 (Controls; Mean age = 48.4 yr)	Quantify the variability of knee motion in patients with medial knee OA	Joint kinematics and kinetics, Knee motion variability, Knee joint laxity, Co-contraction index	Patients with medial knee OA displayed altered kinematics and kinetics
Kiss <i>et al.</i> ^[68] , 2011	n = 90 (Older adults with moderate or severe OA; Mean age = 68.9 yr) n = 20 (Controls; Mean age = 70.7 yr)	To clarify how the variability of gait parameters is influenced by the severity of knee OA	Gait variability: Stride length, Stride width, Speed, Cadence, Duration of double-support, Duration of support	1. Variability of gait associated with knee OA is gender-dependent 2. Severity of OA affects step length, duration of support and cadence

Older adults following total knee arthroplasty Kiss <i>et al</i> ^[60] , 2012	To evaluate the influence of different surgical techniques on gait variability and stability To evaluate treadmill walking at various speeds in OA patients pre- and post-TKA, to assess dynamic stability and variability of sagittal knee movements	Gait Variability: Stride length, Stride width, Speed, Cadence, Duration of double-support, Duration of support	1. Type of surgical technique influences gait variability and stability 2. Differences in the variability of angular parameters predict gait instability and increased risk of falling after TKA
Fallah-Yakhdani <i>et al</i> ^[61] , 2010	(Older adults with TKA; Mean age = 62.3 yr) and post-TKA, to assess dynamic stability and variability of sagittal knee movements	Knee motion variability as measured by the angular velocity of sagittal knee movements; Walking speed; and Variability of knee movements	After TKA, knee motion variability decreased and was related to a reduction of fall risk. Stability control was also improved after surgery
Fallah-Yakhdani <i>et al</i> ^[60] , 2012	To identify the determinant of co-contractions during gait in patients with knee OA before and 1 year after TKA	Gait speed at seven different speeds (0.6-5.4 km/h) EMG activity Variability of angular velocity of sagittal knee movements over the first 30 strides at each speed	1. Variability of sagittal plane knee movements (measured in deg/s) increased with speed; 2. Pre-operatively, the patients' affected and unaffected legs were less variable than those of the young controls and the affected leg was less variable than the healthy peers 3. Post-operatively, variability in the knee OA group was further decreased to a level significantly below both control groups

CV: Coefficient of variation; OA: Osteoarthritis; TKA: Total knee arthroplasty; STV: Stance time variability; CNS: Central nervous system.

tion. Fallah-Yakhdani *et al*^[11] also showed reduced variability during level walking in a study of individuals with OA before and after TKA. In this study, measurements of the variability in knee angular velocity in the sagittal plane before and at 1 year following TKA were performed. The results showed a positive correlation between reduced stride-to-stride variability and reduced risk of falling, and pre-operatively, OA subjects had reduced variability, which was even more pronounced post-operatively, compared to the healthy controls. The pre-operative findings, which appear contrary to expectations, were hypothesized as being the results of a strategy to avoid falling, as opposed to a sign of pathology. The authors, however, did not have a definitive explanation for the continued decline in variability post-operatively. Even so, these results were supported by findings by Kiss *et al*^[60], who found that in individuals with unilateral OA, variability of articular motion decreased post-operatively compared to healthy controls, and similarly, Smith *et al* (unpublished data from the author's lab) showed that gait variability, as assessed by the CV of STV, declined in subjects with OA from the pre- to 6 mo post-operative time points and was significantly lower than a group of healthy controls at the 6 mo post-operatively. Although it is recognized that the specific measures of variability were different between these studies, the relevance of the findings are not diminished in that there appears to be a consistent pattern of decreased movement variability post-TKA relative to pre-operative values and healthy controls.

DISCUSSION

Based on the current evidence, both motor output and movement variability appear to be underappreciated outcome measures that could be linked to physical function both pre- and post-operatively. The evidence in elderly individuals, as well as in those with OA trends toward greater variability equating to greater mobility impairments. However, the alternative question of whether reduced variability, *i.e.*, variability that is less than a healthy, age-matched cohort, also indicates pathology remains unanswered. While data are present that suggest a trend toward reduced motor output and gait variability following TKA, this has not been correlated with functional outcomes, and in fact, some data suggest that reduced variability is associated with a reduced fall risk. Yet, this correlation is only present in older adults with and without OA prior to surgery; the relationship following TKA has not been established.

The question of reduced variability is an interesting one, in that it appears there may be a natural frequency for which individuals move, which serves a specific strategy to optimize balance and proprioception, and reduce the risk of falling. This strategy is likely affected by a variety of factors that may include age, sex, strength, activity level, and degree of pathology.

When considering the ability to respond to sudden balance perturbations, such as those that may occur when walking down stairs, it is theorized that a greater flexibility and available range of motion may be beneficial, thus suggesting that variability that is less than a group of healthy, age-matched controls, may equate to some level of pathology as well. Another potential explanation for the reduced variability following TKA is the influence of co-contraction of antagonist muscles during movement^[10]. Evidence suggests that in individuals with medial knee OA, co-contraction is used as a stabilization strategy during gait to reduce joint excursions. However, this level of co-contraction does not persist following surgery; Fallah-Yakhdani *et al*^[70] showed that following TKA, co-contraction is similar to that of healthy controls. Although, additional analysis revealed a negative regression between the affected side variability and unaffected side co-contraction time, leading the authors to surmise that at least some relationship exists between increased co-contraction and decreased variability. Thus, while it makes sense that this strategy may persist post-operatively, the correlation is notably weak and suggests the influence of other potential mechanisms to control motion and improve balance, when the quadriceps have not yet achieved a level of strength that is commensurate with age-matched controls.

When considering knee implant design, the obvious rigidity of the joint compared to a natural joint may impair the ability to respond to rapid perturbations and hence, may reduce movement variability, although, this cannot be elucidated from the available data. Nonetheless, the development of knee implant designs that incorporate greater range of motion in all planes lends support for this theory and may provide a way to test this hypothesis in the future.

CONCLUSION

Muscle force output and movement variability are important outcome variables that can be used to understand the effects of not only pathological conditions, but surgical interventions such as TKA as well. Movement variability has implications for identifying those at risk of future mobility deficits, fall risk, as well as correlating with severity of OA. In both elderly individuals and those with OA, increased motor output variability tends to implicate greater pathology, which would imply that greater variability, particularly during level walking, has a negative impact on physical function. While the evidence mostly supports this conclusion, it does not answer the question of how reduced variability, below that of an age-matched group of controls, may relate to the same deficits. There are limited data in individuals with knee OA who have undergone TKA, but research that has investigated this population, shows a general trend of reduced post-operative MFS and variability during level walking compared to healthy, age-matched controls. Indeed, if the variability in healthy, age-matched population is considered normal or ideal to optimize mobility function and efficiency, the re-

duced variability in a TKA population may imply impairment, similar to those with greater variability. Additional research investigating this link may provide an important rehabilitation target, or direct development of different implant designs.

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