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The associations of knee extensor muscle steadiness with maximal voluntary torque and physical function in patients with knee osteoarthritis

Anuja P. Satam [a], Marike van der Leeden [a,b], Arjan de Zwart [a], Simon Verberne [a], Jim C. Schrijvers [b], Michelle Hall [c], Joost Dekker [b], Willem F. Lems [a,d], Jaap Harlaar [e,f], Martin van der Esch [a,g,*]

[a] *Reade Centre for Rehabilitation and Rheumatology, Amsterdam, the Netherlands*
[b] *Amsterdam UMC, Vrije Universiteit Amsterdam, Department of Rehabilitation Medicine, Amsterdam Movement Sciences, de Boelelaan 1117, Amsterdam, the Netherlands*
[c] *Centre for Health, Exercise and Sports Medicine, Department of Physiotherapy, School of Health Sciences, The University of Melbourne, Melbourne, VIC, Australia*
[d] *Amsterdam UMC, Vrije Universiteit Amsterdam, Department of Rheumatology, Amsterdam, the Netherlands*
[e] *Delft University of Technology, Department of Biomechanical Engineering, Delft, the Netherlands*
[f] *Erasmus Medical Centre, Department of Orthopaedics, Rotterdam, the Netherlands*
[g] *Centre of Expertise Urban vitality, Amsterdam University of Applied Sciences, Faculty of Health, Amsterdam, the Netherlands*

A R T I C L E I N F O

Keywords:
Knee osteoarthritis
Muscle steadiness
Muscle torque
Physical function

A B S T R A C T

Background: Muscle weakness is characteristic of knee osteoarthritis. Muscle steadiness may be an important adjunct to knee muscle strength in improving physical function in knee osteoarthritis. However, the role of muscle steadiness is uncertain.
Aims: To determine the associations of knee extensor muscle steadiness with maximal voluntary torque and physical function in patients with knee osteoarthritis.
Methods: Baseline data from 177 patients in a randomized clinical trial were used. Isokinetic knee extension torque was processed into maximal voluntary torque [Nm]. Muscle steadiness was expressed as the coefficient of variance [%] and as peak power frequency [Hz]. Physical function was assessed using the Western Ontario and McMaster Universities Osteoarthritis Index, the Get-Up-and-Go and Stair-climb tests. Associations were determined using regression analyses and adjusted for confounders.
Findings: Lower muscle steadiness (i.e., higher coefficient of variance and peak power frequency) was associated with lower maximal voluntary torque ($B = -7.38$, [−10.8, −3.95], $R^2 = 0.10$ and $B = -14.71$, [−28.29, −1.13], $R^2 = 0.03$, respectively). Higher coefficient of variance was associated with lower self-reported physical function ($B = 1.14$, [0.11,2.17], $R^2 = 0.03$) and remained significant after adjusting for potential confounders. Peak power frequency was not associated with physical function.
Interpretation: Low muscle steadiness was weakly associated with low muscle strength and poorer self-reported physical function. Muscle steadiness and muscle strength seem to be different attributes of muscle function. There is no convincing evidence that muscle steadiness is an important adjunct in studying physical function in patients with knee osteoarthritis.

1. Introduction

Knee osteoarthritis (OA) is characterised by limitations in physical function (Van der Esch et al., 2006). For efficient performance of daily physical functioning an adequate, but unknown amount of muscle strength is required (Hortobágyi et al., 2004). Decline in muscle strength is a common feature of knee OA with as much as 60% deficit when compared to healthy subjects (Hortobágyi et al., 2004; Palmieri-Smith et al., 2010; Ploutz-Snyder et al., 2002; Roos et al., 2011; Slemenda et al., 1997; Van der Esch et al., 2006). Traditionally, muscle strength is quantified by maximal voluntary torque (MVT) on a torque-time curve. Fluctuations on a torque-time curve depict the precision and control of voluntary muscle contraction which are not measurable by MVT (Bryant et al., 2009a; Christou, 2011a). Precision and control of voluntary

* Corresponding author at: Reade Centre for Rehabilitation and Rheumatology, PO Box 58271, 1040 HG Amsterdam, the Netherlands.
E-mail address: m.vd.esch@reade.nl (M. van der Esch).

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movement is determined by motor output variability (Baltzopoulos and Brodie, 1989; Christou and Carlton, 2001; Clark et al., 2007; Enoka et al., 2003; Hortobágyi et al., 2004; Jones et al., 2002; Pua et al., 2015; Tracy and Enoka, 2002) and is termed as muscle steadiness (Bryant et al., 2009a; Christou, 2011a; Christou and Carlton, 2001). Mathematically, muscle steadiness is expressed by calculating the magnitude of fluctuations seen in the torque-time curve along the y-axis and the frequency of those fluctuations along the x-axis (Christou and Carlton, 2001; Enoka et al., 2003) (Fig. 1). The extent of the fluctuations depicts coactivity of both agonist and antagonist muscles thereby providing information on muscle function such as smoothness and accuracy of muscle contraction (Bennell et al., 2013; Clark et al., 2007; Hirokawa et al., 1991; Pua et al., 2010; Pua et al., 2015; Tracy et al., 2004; Tracy and Enoka, 2002; Williams et al., 2001; Yoshitake et al., 2007). Higher magnitude and higher frequency of fluctuations on the torque-time curve indicate low muscle steadiness.

Studies on the association of muscle steadiness and muscle strength are limited. In patients with knee OA muscle steadiness and muscle strength were not associated (Hortobágyi et al., 2004), thereby suggesting muscle steadiness and muscle strength capture different attributes of muscle function. However, these findings conflict those in other populations including those with anterior ligament deficiency and hip OA (Pua et al., 2010; Pua et al., 2015). Muscle steadiness has been associated with a summation of performance based physical function test scores. These tests include level walking, stair ascent and descent and Get-up-and go. However, association of muscle steadiness with each of these physical function tests separately is unknown (Hortobágyi et al., 2004). Since near maximal knee muscle strength seems to be required in older persons to perform activities of daily living (Hortobágyi et al., 2003), it is possible that other attributes of muscle function, such as muscle steadiness, may be important in the performance daily physical functions among knee OA patients. Therefore, the aims of this study were to determine the association of knee extensor muscle steadiness with MVT and physical functioning in patients with knee OA.

2. Methods

2.1. Study design

A cross-sectional study was conducted using baseline data of patients who participated in the VIDEX randomized controlled trial (de Zwart et al., 2022). The VIDEX trial has been approved by the medical ethical committee (trial registration number, NL47786.048.14; EudraCT Number: 2014–000047-33). Data of 177 patients (70 males and 107 females, aged 67.6 ± 5.8) were used in the study, of which 5 were later excluded due to missing data. The data consist of muscle strength testing, demographics and clinical scores collected during the baseline measurement. Prior informed consent was obtained from patients for participation in the VIDEX trial and collection and use of data for the study. All patient data were encrypted and stored at the experiment location, Reade, Jan van Breemenstraat, Amsterdam, the Netherlands.

2.2. Measurements

2.2.1. Muscle steadiness and muscle strength

Isokinetic muscle contraction testing was performed on an isokinetic dynamometer (EnKnee Delft instruments Enraf-Nonius, Rotterdam, the Netherlands) (Baltzopoulos and Brodie, 1989). The experiment protocol used an angular velocity of 60°/s and knee extension range-of-motion was set between 80 and 20° of knee flexion. Angular velocity at 60°/s was chosen to maximise the isokinetic period during which the limb moves at a constant velocity (Pua et al., 2015). Patients were instructed to perform extension contractions at maximal intensity. One warm-up trial was performed, followed by a minimum of four measurement trials per patient. Three trials with the highest peak strength were exported to Matlab R2017b (MathWorks, Portola Valley, USA) for processing.

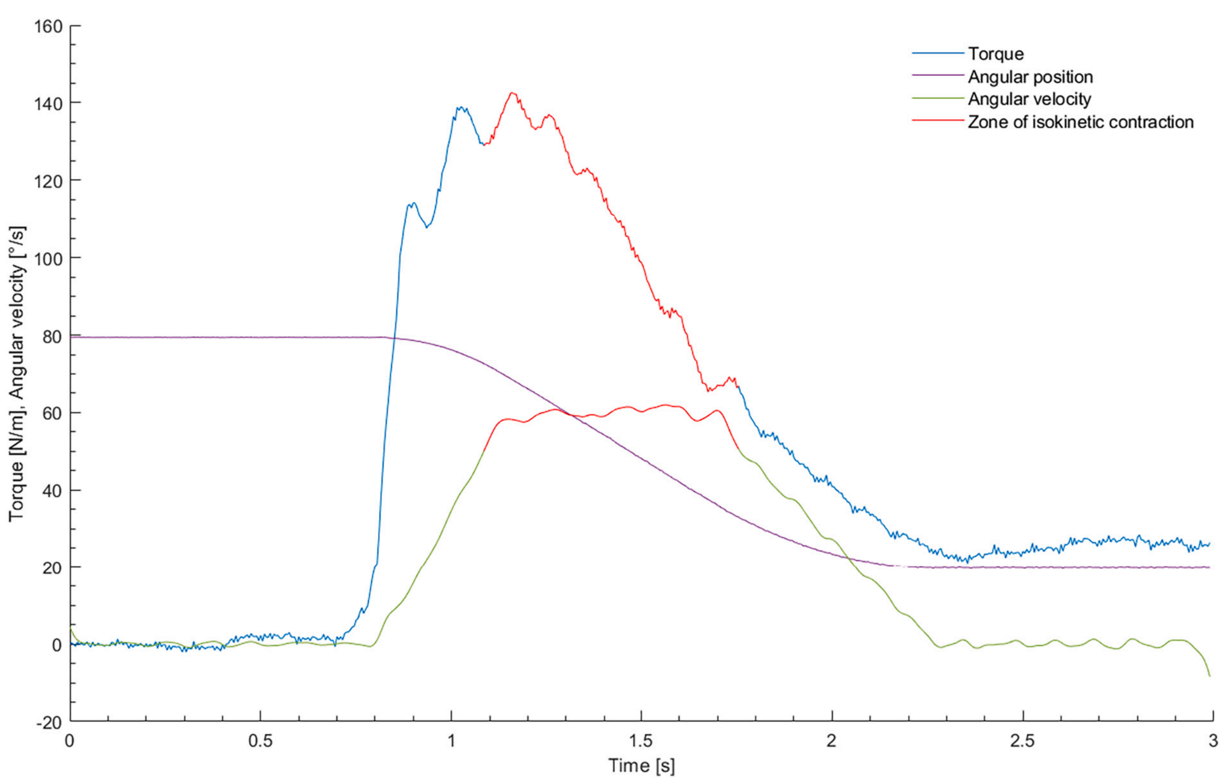

Fig. 1. An example of a torque time curve from a patient in this study. Isokinetic Torque Curve - Definitions: (a) Torque - Force of quadriceps measure during isokinetic dynamometry, (b) Angular position – Position of lower leg throughout the extension movement, (c) Angular velocity – Derived velocity of extension movement, (d) Zone of isokinetic contraction – Torque obtained within the zone of isokinetic velocity of roughly 60°/s.

In order to obtain true isokinetic data, torque produced only during a near constant angular velocity of 60°/s was extracted for further analysis. The torque-time curves were visually inspected and discarded if mechanical errors, trial errors or noise were found in the torque signal. Because the fluctuation patterns seen on a torque curve are specific to that torque curve, one out of the three torque-time curves was selected based on the highest value of MVT instead of average values of three trials.

2.2.2. Muscle torque steadiness

The amplitude and frequency of fluctuations in the torque-time curve were analysed (Fig. 2). Using MATLAB, the torque signals were detrended to eliminate signal slope and a band-pass filter of 2–15 Hz was applied to eliminate gross changes in torque arising from task dynamics (Singh et al., 1920). Along the y-axis, the amplitude represents magnitude of torque fluctuations. This was measured as coefficient of variance (CV) of isokinetic torque, in percentage (%). CV was calculated by obtaining standard deviation from the filtered torque and mean from the raw torque. This avoided a zero-mean value of the filtered torque (See Filtered torque in Fig. 2). Along the x-axis, the frequency of fluctuations within the filtered torque signals were analysed. A Fast Fourier Transform (FFT) function displays the content and power of frequencies present in the signal. The frequency with the highest power was defined as the peak power frequency (PPF) (Fig. 3). PPF, expressed in Hertz (Hz), was the second variable of muscle steadiness.

2.2.3. Maximal Voluntary Torque

The maximal voluntary torque was defined as the peak value of the torque curve, expressed in Newton-metres (Nm).

2.3. Physical function

Tests of physical function were conducted by trained research assistants. The following measurements of physical function were used.

2.3.1. WOMAC-PF scale

The Dutch version of the WOMAC Physical Function Scale was used to assess self-reported functional ability (Roorda et al., 2004). The WOMAC-PF, with a possible score range of 0–68, includes 17 items related to physical function (Bellamy et al., 1988). Each item is scored on a 5-point Likert scale. Higher scores on the WOMAC-PF represent greater limitations in function. Reliability and validity of the WOMAC have been established (intra-test ICC = 0.96) (McConnell et al., 2001; Roorda et al., 2004).

2.3.2. Get Up and Go test (GUG)

The GUG test was performed as previously described by Hurley et al. (1997) (Hurley et al., 1997). To perform the test, patients were seated in a standard-height chair with armrests. On the command “go” patients stood up without help of their arms and walked along a level, unobstructed corridor as fast as possible. A stopwatch was used to measure time taken by the patient to get up from the chair and walk 15 m. The GUG test is reported to be reliable for clinical use (Intra-test ICC = 0.98) (Fitzgerald et al., 2004; Piva et al., 2004).

Stair-climb Up (SCU) and Down (SCD) tests. For the stair climb tests, participants were asked to ascend and descend 12 steps (17 cm in height) as “quickly as possible, but safely”. If needed, use of a handrail for safety was allowed. The stair climb test was expressed as time taken – in seconds – to climb stairs (12 steps). A stopwatch was used to record the time taken. The test-retest reliability (ICC = 0.90) is excellent in patients with advanced hip and knee OA (Dobson et al., 2017).

2.4. Demographics

Sex, age, body mass index (BMI), duration and laterality of knee OA were obtained from the database of the VIDEX trial. In addition, clinical

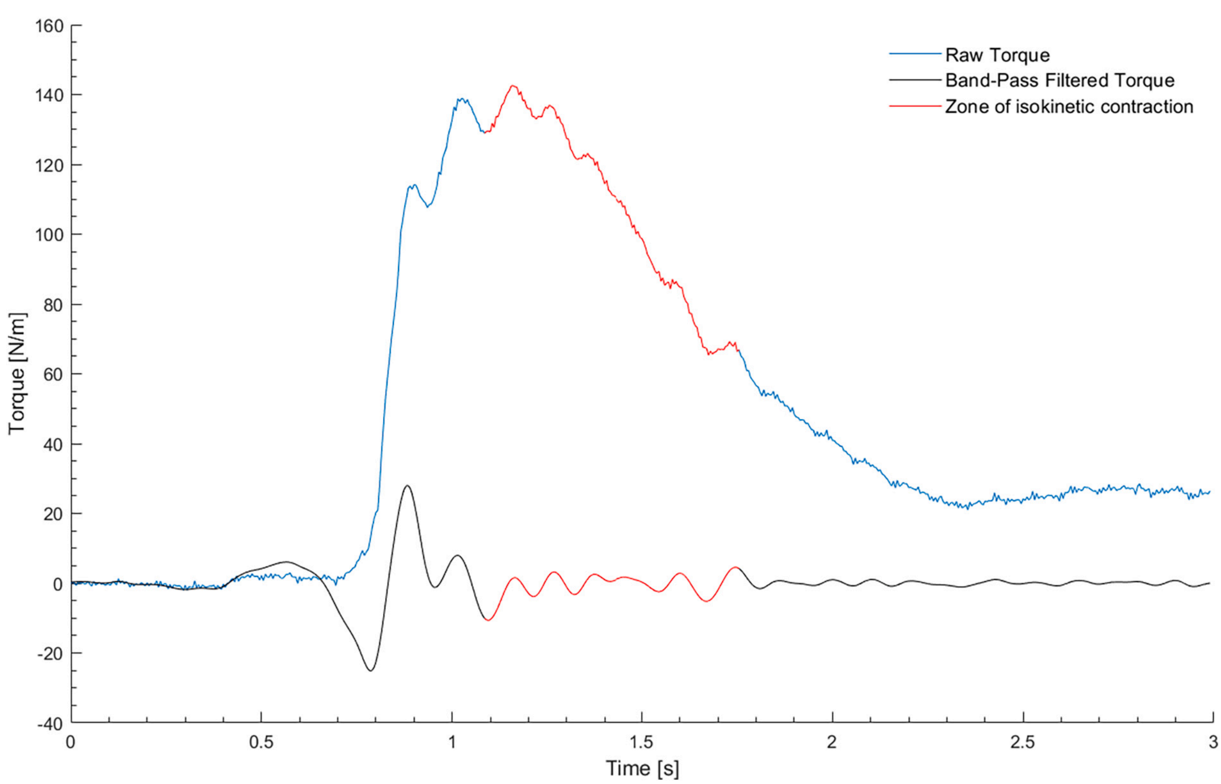

Fig. 2. Obtaining Torque Fluctuations. (a) Originally recorded torque curve in blue, (b) Torque after filtering to isolate fluctuations in black, (c) Red segments indicating zone of isokinetic contraction at a velocity of 60°/*sec*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

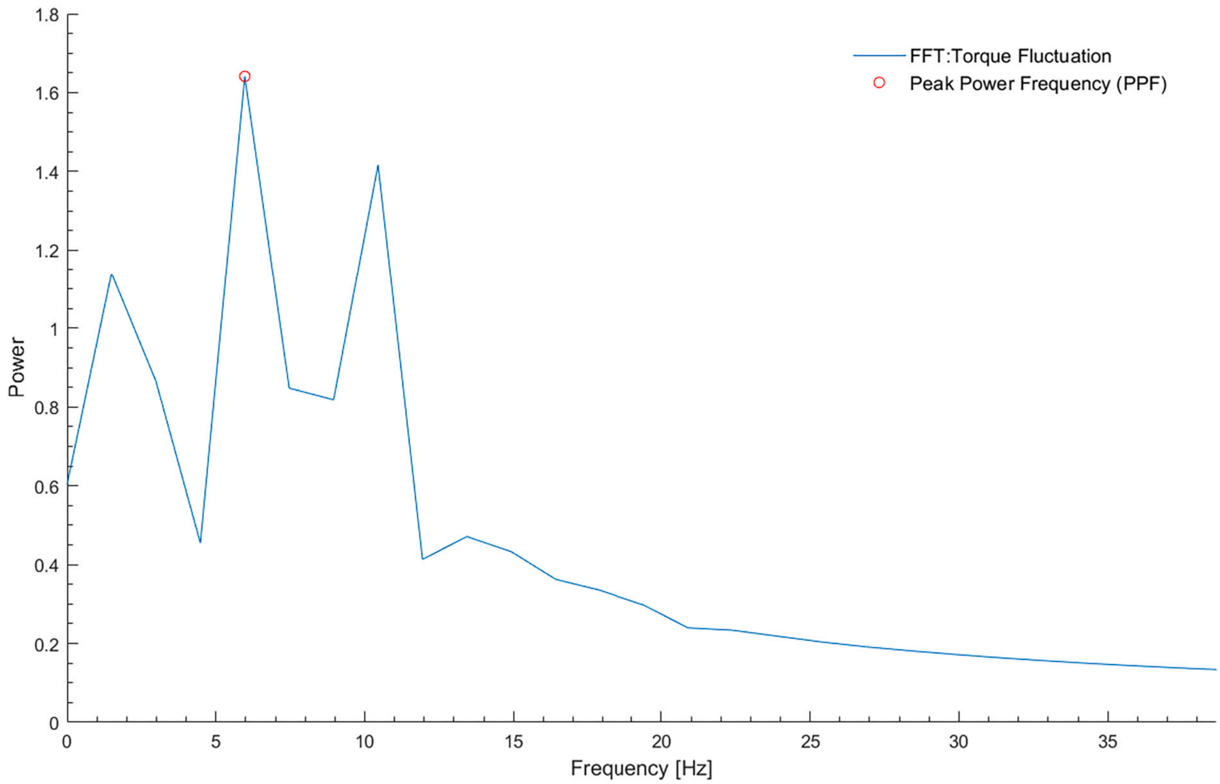

Fig. 3. Fast Fourier Transform (FFT) displays frequency content of fluctuations in the torque curve. The frequency with the highest power is the Peak Power Frequency (circled).

data such as knee pain, radiographic severity of OA, alignment of the hip-knee-ankle angle and index knee were also acquired from the VIDEX database.

2.5. Knee pain

Average knee pain in the past week was measured using a Numeric Rating Scale (NRS) with 0 indicating "no pain" and 10 indicating"worst pain imaginable" (Haefeli and Elfering, 2006).

Radiographic severity of OA.

Severity was scored in a blinded fashion by an experienced radiologist using the grading scales from 0 to 4 proposed by Kellgren and Lawrence (KL) which associate with increasing severity of OA, with Grade 0 signifying no presence of OA and Grade 4 signifying severe OA (Kellgren and Lawrence, 1957; Kohn et al., 2016).

2.6. Alignment of the Hip-knee-ankle angle

Hip-knee-angle data was obtained from the VIDEX database. Within the VIDEX trial, alignment of the knee in the frontal plane was assessed during physical examination by the trained research assistant with a goniometer with the knees extended in a standing position. The frontal plane angle of the knee (hip–knee–ankle angle) in varus or valgus direction from neutral alignment was measured. Alignment of 5° or more in varus or valgus direction was noted.

2.7. Index knee

For the purpose of extension torque testing, one leg/knee was selected. The knee selected for analysis was named the index knee. The index knee was the knee with a greater severity of pain in the previous week. For bilaterally equal severity of pain, a random knee was selected as the index knee.

2.8. Statistical analysis

All variables were checked for missing values, distribution and outliers. First, univariate regression analyses were performed. CV and PPF were the independent variables and MVT and physical function measures (i.e., WOMAC-PF, GUG, SCU and SCD) were the dependent variables. Second, multivariate regression analyses were performed with each covariate – sex, age, BMI, knee pain, KL-grade and knee alignment. A covariate was considered to confound an association if the unstandardized regression coefficient between the independent and dependent variable changed by >10% and was retained in the second model (Van der Esch et al., 2013). A third regression analysis was performed including all covariates to account for all possible effects of the covariates. All statistical analyses were conducted using IBM – SPSS version 25.0 (Endicott, USA).

3. Results

Demographic and clinical characteristics of the patient population are shown in Table 1. Among the 177 patients within the VIDEX trial, baseline muscle strength data of 5 patients were missing and therefore these patients were excluded from analysis. PPF displayed a clustered, non-normal distribution such that approximately two equal sized clusters were seen under 2 Hz and above 2 Hz. Hence it was decided to arbitrarily dichotomise PPF at 2.00 Hz into frequency groups of $\leq$2.00 Hz and > 2.01 Hz.

3.1. Association of muscle steadiness (CV and PPF) with MVT

Univariate linear regression analysis, of CV with MVT showed a significant, negative association (B = −7.38 [−10.80, −3.95], $p < 0.01$, $R^2 = 0.10$). Sex confounded the multivariate model and the association of CV with MVT remained significant after adjustment (B = − 4.83 [−7.47, −2.19], $p < 0.01$, $R^2 = 0.48$). A third regression model of CV

Table 1
Demographic and clinical characteristics.

Characteristic	N (%)	Mean (SD)
Age		67.6 (5.8)
Sex:		
Male	70 (39.5%)	
Female	107 (60.5%)	
Duration of Knee OA [years]		9.2 (9.1)
Body Mass Index (BMI) ($N = 176$)		28.2 (4.4)
Knee Pain (NRS) 0–10 scale ($N = 175$)		4.8 (2.5)
K/L grade (N = 176):		2.0 (1.0)
Grade 0	4 (2.3%)	
Grade 1	65 (36.9%)	
Grade 2	56 (31.8%)28 (15.9%)	
Grade 3	28 (15.9%)	
Grade 4	23 (13.1%)	
Knee Alignment ($N = 174$):		
>5%	112 (64,46%)	
<5%	62 (35.6%)	
Maximal Voluntary Torque [Nm]	172	99.2 (45.1)
Male		135.4 (43.2)
Female		74.9 (26.1)
Maximal Voluntary Torque [Nm/kg]	172	1.20 (0.5)
Co-efficient of Variance (CV) [%]	172	3.2 (1.9)
Male		2.8 (1.5)
Female		3.4 (2.1)
Peak Power Frequency (PPF) [Hz]:	172	2.6 (1.7)
<2.0 Hz	79 (45.9%)	
2.01–4.0 Hz	74 (43.0%)	
4.01–6.0 Hz	14 (8.1%)	
6.01–8.0 Hz	1 (0.6%)	
+8.01 Hz	4 (2.3)	
WOMAC-PF score	174	20.9 (13.1)
Get-Up-and-Go Test [s]	175	10.4 (2.7)
Stair-climb test [s]	175	
Up	175	6.6 (3.3)
Down	175	7.1 (4.0)

WOMAC-PF - Western Ontario and McMaster Universities Osteoarthritis Physical Function Index.
K/L - Kellgren/Lawrence.
N - Number.
SD – Standard Deviation.

with MVT included all covariates and remained significant (B = −4.54 [−7.09, −1.99], $p = 0.01$, $R^2 = 0.54$).

Univariate regression analysis of PPF with MVT showed a significant negative association of PPF with MVT (B = −14.71 [−28.29, −1.13], $p < 0.05$, $R^2 = 0.03$). Sex and alignment confounded the multivariate model and the association remained significant after adjustment (B = −11.45 [−21.65, −1.25], $p < 0.05$, $R^2 = 0.45$). A third regression model of PPF with MVT included all covariates and remained significant (B = −10.375 [−20.26, −0.49], $p < 0.05$, $R^2 = 0.52$).

3.2. *Associations of muscle steadiness (CV and PPF) with physical function*

CV: Univariate linear regression analysis showed a significant association of CV with WOMAC-PF (B = 1.14 [0.11, 2.17], $p < 0.05$, $R^2 = 0.03$). BMI and knee pain confounded the multivariate model and the association remained significant after adjustment (B = 1.02 [0.16,1.89], $p < 0.05$, $R^2 = 0.32$). A third regression model of CV with WOMAC-PF included all covariates and remained significant (B = 0.89 [0.03, 1.75], $p < 0.05$, $R^2 = 0.37$).

Univariate regression analyses of CV with Stair Climb Down test showed significant association (B = 0.31 [0.08, 0.60], $p < 0.05$, $R^2 = 0.02$). Sex and BMI confounded the multivariate model and the association of CV with SCD approached significance (B = 0.28 [0.01, 0.60], $p = 0.05$, $R^2 = 0.14$).

In the third regression model including all confounders, the association of CV with SCD was no longer significant (B = 0.24 [−0.05, 0.52], $p = 0.10$, $R^2 = 0.20$). CV was not associated with the GUG test and SCU test in either the unadjusted or adjusted models (Table 2).

PPF: Univariate regression analysis of PPF with WOMAC-PF, GUG and Stair Climb tests were not significant (Table 2).

No considerable significant interaction effects were found in all analyses of muscle steadiness with MVT and physical function.

4. Discussion

This study aimed to determine the association of knee extensor muscle steadiness (CV and PPF) with maximal voluntary torque (MVT) and with physical function (i.e., WOMAC-PF, GUG, SCU and SCD) in patients with knee OA. Lower muscle steadiness, as indicated by both higher magnitude (CV) and higher frequency of torque fluctuation (PPF), were associated with lower MVT, however the associations were weak. The weak association between muscle steadiness (both CV and PPF) and MVT suggests that muscle steadiness and muscle strength capture different attributes of muscle function. Lower muscle steadiness as indicated by higher magnitude of torque fluctuations (i.e., CV) was weakly associated with WOMAC-PF but not with performance-based physical functioning. Frequency of torque fluctuations (i.e., PPF) was not associated with any measure of physical function. Therefore, the clinical relevance of muscle steadiness among knee OA patients seems questionable given absence of association with performance-based physical function, and the weak association with self-reported physical function.

4.1. *Muscle steadiness and maximal voluntary torque (MVT)*

The results of this study showed that a low maximal voluntary torque is associated with a low muscle steadiness, expressed by a high magnitude of fluctuations (i.e., high CV) and a high frequency of fluctuations (i.e., high PPF). Conflicting results have been reported in previous studies (Hortobágyi et al., 2004; Pua et al., 2010; Pua et al., 2015). No association has been reported ($R = -0.13$) of muscle steadiness with muscle strength among 20 patients with knee OA (Hortobágyi et al., 2004), while a moderate to strong association has been reported among 87 patients with anterior cruciate ligament (ACL) injury ($R = -0.41$) (Pua et al., 2015) and 67 patients with hip OA, respectively ($R = 0.69$) (Pua et al., 2010). Differences exist between the present and other studies (Hortobágyi et al., 2004; Pua et al., 2010; Pua et al., 2015) in sample size, patient characteristics, type and intensity of muscle contraction, and method of calculating muscle steadiness. The comparatively smaller sample size of 20 patients with knee OA could explain the absence of the association between muscle steadiness and MVT in the study of Hortobagyi et al. (Hortobágyi et al., 2004). When compared to associations reported by Pua et al. among patients with ACL injury (Pua et al., 2015), our results are weaker. This could be explained by the difference in patients' characteristics: knee OA patients in our study versus relatively young ACL patients (Pua et al., 2015), knee OA patients of our study exhibited significantly lower muscle strength (MVT = 99.2 ± 45.1 [Nm] or 1.2 ± 0.5 [Nm/kg]) when compared to patients with ACL injury (MVT = 2.1 ± 0.5 [Nm/kg]). Given the low knee extensor strength, it could therefore be possible that higher magnitude and frequency of fluctuations in patients of knee OA could be an attempt to produce steady contractions (Bryant et al., 2009a). It has been reported that altered quadriceps steadiness may be the result of diminished quadriceps activity and relatively higher hamstring activity among knee OA patients (Hortobágyi et al., 2005). Higher co-contraction, or higher hamstring activity may therefore be present in patients with knee OA in this study in order to maintain a given joint torque. However, this was not assessed in our study. Lastly, type and intensity of muscle contractions could explain the differences in the results. Summing up three types of contractions (Hortobágyi et al., 2004), namely isometric, concentric and eccentric contractions into a single outcome may reduce variability and therefore the strength of an association. Based on these results and our results there is some evidence

Table 2
Regression analysis of CV and PPF on MVT, WOMAC-PF, 6MWT, GUG, SCU, and SCD.

	CV, magnitude of variance in MVT (%)						PPF, frequency of variance in MVT (Hz)				
	B	SE	β	C.I. [,]	*p*		B	SE	β	C.I. [,]	*p*
MVT											
Model 1	−7.38	1.73	−0.31	−10.8, −3.95	0.000	Model 1	−14.71	6.89	−0.16	−28.29, −1.13	0.034
Model 2 (Sex)	−4.83	1.34	−0.20	−7.47, −2.19	0.000	Model 2 (Sex, Alignment)	−11.45	5.17	−0.13	−21.65, −1.25	0.028
Model 3	−4.54	1.29	0.19	−7.09, 1.99	0.001	Model 3	−10.38	5.01	0.12	−20.26, −0.49	0.040
WOMAC-PF											
Model 1	1.14	0.52	0.17	0.11, 2.17	0.030	Model 1	1.70	2.01	0.66	−2.24, 5.64	0.400
Model 2 (BMI, Pain)	1.02	0.44	0.15	0.16, 1.89	0.020						
Model 3	0.89	0.44	0.13	0.03, 1.75	0.043						
6MWT											
Model 1	−2.62	3.49	−0.06	−9.50, 4.26	0.453	Model 1	−25.20	13.13	−0.15	−57.12, 0.72	0.057
						Model 2 (Pain, Alignment)	−17.65	12.61	−0.10	−42.54, 7.24	0.163
						Model 3	−16.16	10.79	−0.09	−37.47, 5.14	0.136
GUG											
Model 1	0.06	0.10	0.04	−0.15, 0.26	0.592	Model 1	0.69	0.38	0.14	−0.07, 1.45	0.075
SCU											
Model 1	0.17	0.13	0.1	−0.08, 0.42	0.183	Model 1	0.7	0.48	0.11	−0.25, 1.64	0.146
SCD											
Model 1	0.31	0.15	0.16	0.008, 0.61	0.044	Model 1	0.66	0.58	0.09	−0.47, 1.80	0.251
Model 2 (Sex, BMI)	0.28	0.14	0.14	0.01, 0.60	0.052						
Model 3	0.24	0.14	0.12	−0.05, 0.52	0.098						

Abbreviations: CV = Coefficient of variance, PPF = Peak Power Frequency,
MVT = Maximal Voluntary Torque,
WOMAC-PF = Western Ontario and McMaster Universities Osteoarthritis Physical Function Index,
6MWT = Six-minute walk test, BMI = Body Mass Index, GUG = Get-Up & Go test, SCU = Stair-Climb Up test,
SCD = Stair-Climb Down test.
Model 1 = univariate analysis.
Model 2 = multivariate analysis.
Model 3 = multivariate analysis with all covariates.

that they measure different attributes of muscle function. It can be speculated that assessing muscle steadiness during concentric and eccentric contractions separately and at a high intensity in a sufficient sample of patients with knee OA can provide a broader understanding of the association.

4.2. Muscle steadiness and physical function

Magnitude of torque fluctuations (i.e., CV) was weakly associated with reported but not performed physical function. Frequency of torque fluctuations (i.e., PPF) was not associated with any measure of physical function. The weak association of CV with WOMAC could be a chance finding. The weak association of CV with WOMAC could be a chance finding, given that muscle steadiness, a performance-based parameter was not associated with any of the performance-based tests, but with self-reported test of physical function, and that this association was weak (R^2 = 0.03). Therefore, it can be stated that the association of muscle steadiness with physical function has questionable meaning. This is in contrast with the study of Hortobagyi et al., who reported a positive association of muscle steadiness with physical function (Hortobágyi et al., 2004). Additionally, an association of muscle steadiness with physical function was also reported in patients with ACL injury and hip OA (Pua et al., 2010; Pua et al., 2015). Apart from the earlier mentioned differences, other factors that could explain the contrasting results include (i) patient and disease characteristics, (ii) methods of testing physical function and (iii) method of calculating steadiness.

(i) Patients in our study exhibited significantly lower knee extensor strength than those in other studies (Hortobágyi et al., 2004; Pua et al., 2010; Pua et al., 2015). For patients with significant impairment in muscle strength, performance of tasks might depend more on the production of adequate muscle strength than on the precision of the strength produced (Pua et al., 2010). Therefore, the degree of muscle strength impairment in the patients in our study may be severe enough to erase any association between muscle steadiness and physical function. Secondly, the contrasting nature of onsets of ACL injury and knee OA could contribute to the differences between the studies, given that ACL injury is a sudden traumatic change, while OA is a chronic degenerative change affecting neuromuscular function gradually (Christou, 2011a; Fink et al., 2007; Mau-Moeller et al., 2017).

(ii) The contrasting results between our study and Hortobagyi et al. (Hortobágyi et al., 2004), could be explained by the way physical function measurements were combined to one single outcome measures which could have influenced the associations. The lack of an association could be explained by the task domains of the performed tests. Especially because of inconsistencies between results of various physical function tests it can be speculated that specific physical function tests, demanding higher muscle coordination and control of the knee joint could be more associated with muscle steadiness.

(iii) The use of an analytic wavelet transform and mean instantaneous frequency might be a more elaborate mathematical approach compared to Fast Fourier transform (Pua et al., 2015), since this approach provides accurate magnitude and phase information in the time-frequency domain (Tracy and Enoka, 2002).

4.3. Scope and limitations

The large number of participants in this study provides a good insight into the relationship between muscle steadiness, muscle strength and physical function in patients with knee OA, however, several limitations of the study exist. Firstly, in the VIDEX randomized controlled trial a control group without exercise interventions was not included and therefore comparison of the results with a group without exercise was not possible. Secondly, the study utilized a sampling frequency of 200 Hz which resulted in a relatively low resolution of data in a given torque signal, such that a highly clustered distribution of PPF was seen (Table 1). Finally, due to its skewed and clustered distribution, PPF was dichotomized into frequencies between 0 and 2 Hz and > 2 Hz which resulted in a loss of information from collapsing all frequencies >2 Hz into one group. It is possible that a non-clustered distribution of PPF and a higher resolution of frequencies as seen in other studies could yield more precise results (Hortobágyi et al., 2004; Pua et al., 2010; Pua et al., 2015; Tracy et al., 2004).

5. Conclusion

Low muscle steadiness was weakly associated with low muscle strength and poorer self-reported PF. Muscle steadiness and muscle strength seem to be different attributes of muscle function. There is no convincing evidence that muscle steadiness is an important adjunct in studying physical function in patients with knee OA.

Declaration of Competing Interest

None.

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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