Title: Association between quadriceps tendon elasticity and neuromuscular control in individuals with knee osteoarthritis

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Abstract

Background:

Knee osteoarthritis is a complex condition with established risk factors such as female sex, increasing age and body mass index, reduced quadriceps muscle strength and knee injury. Despite known associated risks, the role and behaviour of knee tendons in knee osteoarthritis remains unclear. This study explores the association between quadriceps tendon elasticity, muscle strength, neuromuscular control, proprioception and patient reported outcome measures in individuals with knee osteoarthritis.

Methods:

Adults with doctor-diagnosed knee osteoarthritis were recruited from rheumatology clinics and general practitioner practices. Quadriceps tendon elasticity was estimated using sonoelastography. Neuromuscular control data including electromyography, electromechanical delay and proprioception measures were included. Participants completed the Knee Injury and Osteoarthritis Outcome Score. Associations between elasticity values, physical and neuromuscular data and patient reported outcomes scores were evaluated using Spearman's correlations.

Findings:

Thirty-nine adults with knee osteoarthritis were eligible for inclusion. Increased tendon stiffness was negatively associated with rate of force development, time to half peak force and passive positioning sense in individuals with knee osteoarthritis. Similarly, patient reported symptoms were found to be associated with sonoelastography findings with moderate-strong associations observed between activities of daily living sport and recreation, pain and symptoms and between neuromuscular control measures and muscle strength.

Interpretation:

Stiffer tendon identified within the knee osteoarthritis group was associated with reduced neuromuscular control and knee joint proprioception. Stiffer quadriceps tendon may contribute to the poorer reported symptoms by knee osteoarthritis individuals. These findings may impact disease symptoms and progression which could lead to further joint impairment.

Keywords:

Knee, osteoarthritis, quadriceps, tendon, sonoelastography, neuromuscular control

1.1 Introduction

Knee Osteoarthritis (KOA) is driven by biological, mechanical and structural factors (Andriacchi et al., 2009; Hunter and Bierma-Zeinstra, 2019). The complex cartilaginous destruction and repair mechanism, combined with neuromuscular and biomechanical influences, continue to generate uncertainty over the principle or varying sources of initiation and/or progression KOA. There have been several established risk factors for the development and progression of KOA (Hunter and Bierma-Zeinstra, 2019). Knee injury is associated with the onset of KOA (Silverwood et al., 2015) with approximately 50% of individuals who suffer anterior cruciate ligament injury developing KOA within 10-15 years (Muthuri et al., 2011; Roos and Arden, 2016). Biological associations such as female sex, increased body mass index (BMI) and ageing, are well-known risk factors for KOA (Glyn-Jones et al., 2015; Hunter and Bierma-Zeinstra, 2019; Kulkarni et al., 2016; OARSI, 2016; Palazzo et al., 2016; Silverwood et al., 2015). Additionally, reduced muscle strength (Culvenor et al., 2017; Øiestad et al., 2022), neuromuscular control alterations (Tayfur et al., 2022) and impaired proprioception (Van Tunen et al., 2018) are also considered to pose a risk to normal joint function, and may contribute to knee joint damage in KOA (Englund, 2010).

Reduced quadriceps muscle strength is a recognised risk factor for the onset of KOA (Heiden et al., 2009; Luc-Harkey et al., 2018; McAlindon et al., 2014; NICE, 2014; Øiestad et al., 2022, 2015; Palazzo et al., 2016; Rice et al., 2011; Roos et al., 2011; Saxby and Lloyd, 2017). Consequently, movement patterns may become affected and quadriceps muscle weakness contributes to faster progression of the disease (Winters and Rudolph, 2014). Individuals with KOA have significantly reduced quadriceps muscle strength compared to their healthy counter-parts, with reported difference in quadriceps muscle strength of 10-76% (Alnahdi et al., 2012). The quadriceps tendon works with the quadriceps muscles to transfer power responsible for knee extension, and the elastic properties of the tendon are linked to the mechanic role of the muscle to which they are attached (Werkhausen et al., 2018). The quadriceps muscle-tendon unit plays a crucial role in knee joint functional tasks such as walking, sitting and loading (Luc-Harkey et al., 2018), and is influenced by both neuromuscular and biomechanical factors.

The knee joint facilitates gait, flexion, and rotation, while maintaining joint stability (Masouros et al., 2010). Neuromuscular control is responsible for muscle response and activation patterns to neural sensory signals, facilitating controlled knee joint movement (Andrade, 2014). Neuromuscular deficits are observed as a result of normal ageing, prompted by a reduction in neural drive, single fibre tension and activation (Takacs et al., 2013). Additionally, individuals with KOA exhibit a reduction in neuromuscular control (Smith et al., 2016). More recently, individuals with severe KOA displayed significantly lower rate of force development (RFD) that those with early KOA (Suzuki et al., 2022). Individuals with KOA have impaired proprioception compared to age-matched healthy controls (Knoop et al., 2011). Reduced proprioception can affect individuals’ knee joint stability and coordination through reduced awareness of lower limb position and motion sense, significantly increasing the risk of falls in individuals with KOA (Bozbas et al., 2017). Comparatively poorer ankle joint proprioception, determined by position matching, is previously reported in individuals with repaired ruptured Achilles tendon (>12months) versus healthy controls (Bressel et al., 2004). Furthermore, a reduction in lower limb proprioception can lead to excess movement outside the normal physiological range (Knoop et al., 2011), and potentially further joint damage. Excessive joint movements and joint instability may be attributed to soft tissue changes such as tendon stiffness, which is currently unexplored.

The viscoelasticity of the muscles and tendon has potential functional importance (Knudson, 2007), where alterations in tendon properties may affect muscle–tendon interaction, energy dissipation (Werkhausen et al., 2018) and range of movement (Ebihara et al., 2020). Structural and mechanical tendon characteristics can be evaluated using sonoelastography (SE) (Dickson et al., 2019) and can be modified through resistive loading (Magnusson et al., 2008; Reeves et al., 2003; Werkhausen et al., 2018; Wiesinger et al., 2015; Yin et al., 2014).

Identifying relationships between tendon and KOA risks, coupled with early detection, may provide opportunity for targeted therapy and improved outcomes. Clinical and Imaging tests are often employed in the detection and management of KOA. Condition specific patient reported outcome measures (PROMs) may be utilised to understand health outcomes directly from the patient perspective and are widely used to support clinical decision making, prioritisation for surgery and evaluating practice (Churruca et al., 2021). Positive correlations between tendon stiffness and PROMs are previously reported within an Achilles tendon study, highlighting the important role and function of tendon in performing daily activities (Laurent et al., 2020) and the need to explore any potential mechanisms between tendon elasticity and painful symptoms. Disease prevention and joint preservation is high priority in the management of KOA, therefore, potentially modifiable components of the disease process should continue to be explored and evaluated (Georgiev and Angelov, 2019; WHO, 2013).

Muscle activation patterns affected by alterations in the proprioception feedback loop, combined with poor muscle strength and poor neuromuscular control, could contribute to knee tendon pathology. Similarly, pathological alterations within the muscle and tendon may reduce muscle function affecting neuromuscular control leading to altered muscle activation patterns necessary to maintain joint stability. Understanding the role of the tendon in this two-way relationship is an important step. Accordingly, this exploratory study seeks to investigate the association between quadriceps tendon elasticity, quadriceps muscle strength, neuromuscular control, proprioception and PROMs in individuals with KOA.

1.2 Methods

Data were drawn from a laboratory-based observational study designed to evaluate neuromuscular control, proprioception and quadriceps tendon elasticity in people with KOA (Dickson et al., 2022; Smith et al., 2019). Data were included based on recruitment eligibility identified in Table 1. The study was approved by West of Scotland research ethics committee (13/WS/0146) and Glasgow Caledonian University, Scotland (HLS12/86) and conducted in accordance with the declaration of Helsinki. All participants provided written informed consent.

Table 1. Participant inclusion and exclusion criteria

Inclusion	• Aged ≥40years to incorporate post-traumatic KOA • KOA diagnosis determined by either: Knee radiograph report KOA International Classification of Diseases (IDC-10) codes Participant expressed GP consultation confirmation of KOA • Ultrasound scan of symptomatic/most symptomatic knee
Exclusion	• Neuromuscular skeletal injury/illness (e.g. Multiple Sclerosis, Parkinson’s disease; Muscular Dystrophy; Cerebral Palsy) • Knee surgery, knee arthroplastic surgery and arthroscopic debridement or corrective surgery for KOA in the past 12 months • Corticosteroid injections to or around the knee in the past 3 months • Unstable heart disease • Insulin-dependent diabetes • Osteoporosis • Falls and other motor deficits • Unable to walk up and down stairs • Unable to rise from a chair without the aid of another person • Unstable medication schedule and medication that causes dizziness • Dementia/ Alzheimer’s/an inability to comprehend, follow instructions and give informed consent • Other rheumatic conditions (e.g. rheumatoid arthritis)

1.2.1 Knee Injury and Osteoarthritis Outcome Score

The Knee Injury and Osteoarthritis Outcome Score (KOOS) was used as a measure of KOA disease severity based on patient reported outcomes. KOOS is a valid and reliable measure for use in KOA populations (Collins et al., 2011; Roos et al., 1998). It is a 42-item questionnaire consisting of 5 separately scored subscales including pain, symptoms, activities in daily living, sport and recreation and quality of life, with lower scores (0-100) depicting more extreme patient reported knee problems (Roos and Lohmander, 2003).

1.2.2 Ultrasound protocol

Tendon elasticity was estimated using sonoelastography measures (colour map scoring; CS and elasticity ratio; ER). Quadriceps tendon sonoelastography measures are reported with fair to excellent reliability when performed by an experienced operator (Dickson et al., 2019). Participants were scanned by an experienced operator using an esaote Mylab 70 XVG, Italy, version EVO 13.60M with multi frequency linear array transducer (LA523, L4-13MHz). Participants were scanned in a seated or lying position with knee supported in flexion using a standardised 30^{O}

pad (Beggs et al., 2010). Using B-mode US, the distal quadriceps tendon (DQT) was located in longitudinal orientation using the base of patella as the distal landmark, and an elastogram performed for a minimum 5 seconds (s) using previously published optimal settings (Havre et al., 2008). A representative static image which demonstrated sufficient stress as demonstrated by the equipment quality indicator was selected to perform image analysis. CS was visually graded using a similar three-point scale employed in previous studies (De Zordo et al., 2010, 2009; Klauser et al., 2013), stiff = 1, intermediate = 2, and soft = 3, depicted by colour map. A small fixed-site reference site region of interest of 1mm was positioned within homogenous pre-femoral fat pad tissue to calculate ER between the distal tendon with higher scores representing stiffer tissue. Detail of scan protocol and analysis is described in full elsewhere (Dickson et al., 2020).

1.2.3 Neuromuscular control measures

1.2.3.1 Electromyography (EMG) and maximal voluntary contraction (MVC)

Trigno sensors (99.9% silver, 4 5x1mm bar sensors, fixed inter-electrode distance 10mm, Delsys, Boston, MA, USA) were placed parallel to the muscle fibres over the muscle belly of the vastus medlais/lateralis (VM, VL) and rectus femoris (RF) muscles of the most symptomatic leg. For MVC measures, participants were secured in a seated position in an isometric dynamometer (KinCom 125H Chateux Inc, Tennesse, USA; Biodex 4Pro, Biodex Medical systems, New York, USA). The test leg was secured by means of a padded shin pad attached to the moment arm with the knee flexed at 50deg (0deg equals full extension) and a hip flexed at 90deg. Following a series of warm-up contractions, participants performed a series of 3 extension MVC's lasting 3s with 30s rest for the hamstrings and quadriceps. EMG data was Butterworth 4th order zero-lag bandpass filtered at 20-450Hz. The average root mean squared amplitude (RMS_{amp}) was calculated over a 500ms window 250ms either side of peak force for the quadriceps muscles. RMS_{amp} was chosen as it is suggested to be one of the more robust and directly linked to electrical power, having more physiological significance over linear envelope(Burden et al., 2003; Konrad, 2006). Full detail of the methods for data collection of EMG and MVC are outlined in Smith et al. (2019)

1.2.3.2 Electromechanical delay

Absolute force recorded from the KinCom/Biodex was utilised to calculate the following variables: electromechanical delay (EMD), calculated as the time delay (milliseconds (ms)) between the onset of electrical activity and the onset of force: EMD (ms) = onset of force - onset of muscle activity and was averaged over 3 trials (Zhou, 1996). The onset of electrical activity and force were defined as the first point when the electrical signal or force constantly exceeds +/- 3 standard deviation (SD), from resting baseline (Mora et al., 2003).

1.2.3.3 Time to half Peak Force, Rate of Force Development and Rate of Relaxation

Time to half PF ($T^{1/2}$PF) was calculated as the time between the onset of force and 50% peak force (PF), averaged over 3 trials. Rate of force development (RFD) was calculated as the change in force divided by the change in time between 25% and 75% PF, and in 25ms epoch from the onset of force (0ms) -100ms (0-25ms, 25-50ms, 50-75ms, 75-100ms) using equation: RFD ($N.S^{-1}$) = $\frac{\Delta \text{ force}}{\Delta \text{ time}}$, and was averaged over 3 trials. Rate of relaxation (RR) was calculated the same way as RFD between 50% PF on the descent and offset of force (where force recedes below 20N).

1.2.4 Proprioception

Passive and active proprioception of the knee was assessed in a custom built instrumented chair (Hurkmans et al., 2007), designed to minimise feedback (Figure 1). Participants were seated with their knee and hip placed at 90^o and 70^o flexion respectively with their tibiofemoral joint space aligned with the moving arms' rotational axis. Ankle air splints were placed and inflated on each leg, before being secured to the moveable calf rest proximal to the Achilles tendon, to minimise proprioceptive stimuli originating from the skin (Supplementary material - Figure 2). Participants performed three proprioception tests in a set order: a) passive motion sense (PMS); b) passive position sense (PPS); and c) active position sense (APS). Proprioception has been shown to demonstrate good inter-rater reliability ICC$_{(2,1)}$ =0.91 and 0.89; and intra-rater reliability ICC$_{(2,1)}$ = 0.91 and 0.86 for KOA and controls respectively (Hurkmans et al., 2007).

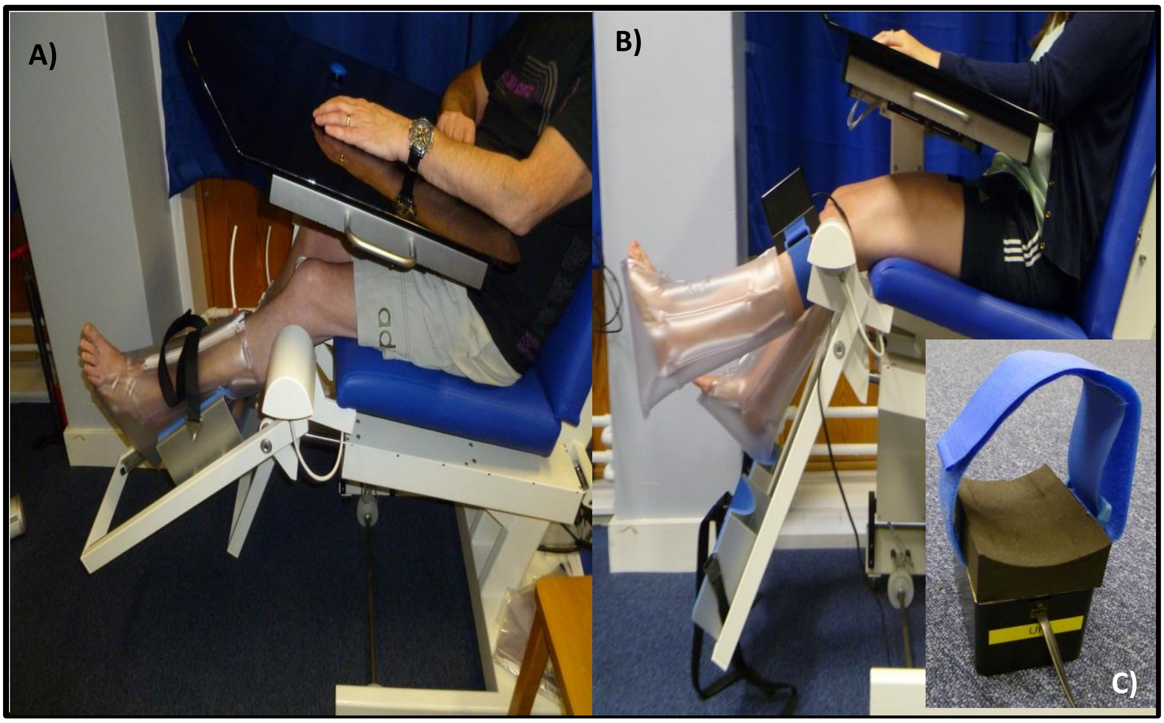

Figure 1. Participant orientation in the proprioception chair A) without APS unit for passive position sense and passive motion sense, B) with the APS unit for the active position sense, C) APS unit.

1.2.4.1 Passive motion sense (PMS)

Passive motion sense (PMS) tests both legs in a random order. Both legs start at 90° flexion, are moved at 4.5°/s to 75° flexion, before being moved at 4.5°/s to 45° flexion (rest angle). An arm was raised to notify participants the rest angle had been reached. After a random delay, the test leg started extending at 0.3°/s. Participants were instructed after a random delay one leg would move once they clearly felt their leg moving they were to push the blue button on the table top corresponding to the leg they felt moving. If participants felt any discomfort or sudden pain in their knee they could push either blue button and the test would stop. The mean of 3 trials, measured as the difference between the rest angle and the angle at which they felt movement was calculated for PMS. A small difference indicated adequate proprioception where a larger difference indicated impaired proprioception, however there are no clear cut-offs which defined impaired state.

1.2.4.2 Passive position sense (PPS)

Passive position sense (PPS) was tested for the test leg only. Both legs started at 90° flexion, and were moved at 4.0°/s to the start position of 75° flexion. The test leg was then moved at 4.0°/s to 30° flexion. An arm was raised to notify participants the test angle had been reached. Participants were instructed to concentrate, 'feel' and remember the test position for 5s. After 5s the leg returned back to the start position at 75°, before extending at 1.0°/s. Participants were instructed to push the blue button once they thought their leg had reached the test angle (30°). The mean of 3 trials, measured as the difference between test angle and the angle the moment the participant pushed the button was calculated for PPS. A small difference indicated adequate proprioception where a larger difference indicated impaired proprioception, however there are no clear cut-offs which defined impaired state.

1.2.4.3 Active position sense (APS)

Active position sense (APS) was similar to PPS. The APS (Figure 2) unit was attached above the tibial tuberosity distal to the patella. Both knees started at 90° flexion, were moved to the start position at 75° flexion, the test leg was then moved to 30° flexion, in line with PPS protocol. An arm was raised to notify participants the test angle had been reached. Participants were instructed to concentrate, 'feel' and remember the test position for 5s, before the leg was returned to the start position. The leg was unstrapped from the chair and participants were instructed to extend their leg (straighten) to the test angle (30°). Once they felt they had reached the angle, stop extending their leg and push the blue button. The mean of 3 trials, measured as the difference between the test angle and the angle the moment the participant pushed the button was calculated for APS. A small difference indicated adequate proprioception where a larger difference indicated impaired proprioception, however there are no clear cut-offs which defined impaired state.

1.2.5 Statistical analysis

Descriptive statistics were used to present participant characteristics and were expressed as either numbers and percentages or means, standard deviation and range as appropriate. Associations between elasticity values and physical and neuromuscular data were evaluated using Spearman's correlations as the appropriate nonparametric test based on the score distribution across the measures of interest. Associations were interpreted from correlation coefficients as follows: ≤0.29, small; 0.30-0.49, moderate and ≥0.50 large (Cohen, 1988). Two-tailed statistical significance was defined as $p \leq 0.05$. Statistical analysis were performed using SPSS (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 24.0. Armonk, n.d.).

1.3 Results

A total of 39 older adult participants (≥40 years old) were included in this study (Table 2).

Table 2. Participant characteristics.

Variables	(n) or mean	(%) or SD	Range
Female	(27)	(69)	n/a
Male	(12)	(31)	n/a
Age (yrs)	61.9	7.58	44.7-79.9
BMI (kg/m^2)	30.36	6.10	21-43
PMS (degrees)	2.50	2.00	0.50-11.67
PPS (degrees)	5.90	3.81	0.67-18.90
APS (degrees)	6.37	5.34	2.53-18.43
Muscle strength (Nm.Kg)	0.57	0.23	0.12-1.16
RFD ($N.S^{-1}$)	0.3603	0.2892	0.01-1.46
RFD (0-25ms)	0.2377	0.1946	0.02-0.95
RFD (25-50ms)	0.3962	0.4459	0.03-2.36
RFD (50-75ms)	0.6428	1.0025	0.03-6.01
RFD (75-100ms)	0.5633	0.5830	0.03-2.99
RFD (25-75ms)	0.4336	0.7052	0.03-4.18
RFD (0-100ms)	0.3828	0.5283	0.03-3.08
RR (ms)	484.50	358.41	53.73-1975.98
$T^{1/2}$PF (ms)	187.41	140.70	17.99-659.34
VM EMD (ms)	118.99	40.45	29.73-204.44
RF EMD (ms)	117.33	44.21	21.15-212.13
VL EMD (ms)	118.64	42.11	22.39-189.50
VM EMG (mV)	0.0411	0.3296	0.001-0.128
RF EMG (mV)	0.0501	0.03419	0.011-0.164
VL EMG (mV)	0.0646	0.05520	0.007-0.205
EMG Mean (mV)	0.0519	0.3723	0.008-0.155
CS	(1=16, 2=10, 3=13)	0.870	1-3
ER	2.65	1.21	1.10-5.70
KOOS pain	55	18	19-89
KOOS Symptoms	55	21	14-93
KOOS ADL	63	21	22-99
KOOS sport and recreation	32	26	0-90
KOOS QoL	39	21	0-88

Data presented as mean (SD, standard deviation) or n (%, percentage), yrs.; years, kg/m^2; kilogram per square meter, BMI; Body Mass Index, PMS, passive motion sense; PPS, passive position sense; APS, active position sense; N.S, newton-second; CS, colour score, RFD, rate of force development; ms, milliseconds; mV, millivolt, RR, rate of relaxation; $T^{1/2}$PF, time to half peak force; EMD, electromechanical delay; EMG, electromyography; VM, vastus medialis; RF, rectus femoris; VL, vastus lateralis, ER; elasticity ratio of the distal quadriceps tendon, KOOS; knee injury and osteoarthritis outcome score, ADL; activities of daily living, QoL; quality of life.

Table 3. Association between distal quadriceps tendon elasticity values, proprioception, neuromuscular control measures and knee injury and osteoarthritis outcome scores in individuals with knee osteoarthritis.

Variables	Colour Score (n=39)		Elasticity Ratio (n=33)	
	r	*sig*	*r*	*sig*
PMS (degrees)	0.030	0.856	0.002	0.993
PPS (degrees)	-0.093	0.573	**-0.441**	**0.010**
APS (degrees)	-0.148	0.368	-0.033	0.857
Muscle strength (Nm.Kg)	-0.018	0.917	-0.006	0.975
RFD (N.S^{-1}) (25-75% MVC)	**-0.344**	**0.032**	-0.195	0.276
RFD (0-25ms)	0.070	0.684	0.189	0.308
RFD (25-50ms)	0.108	0.530	0.127	0.496
RFD (50-75ms)	0.081	0.638	0.121	0.517
RFD (75-100ms)	0.083	0.632	0.200	0.281
RFD (0-100ms)	0.114	0.508	0.160	0.390
RR (ms)	0.035	0.831	-0.097	0.592
T$^{1/2}$PF (ms)	**-0.363**	**0.023**	-0.322	0.068
VM EMD (ms)	0.064	0.717	0.188	0.320
RF EMD (ms)	0.124	.0483	0.279	0.135
VL EMD (ms)	0.153	0.388	0.122	0.521
VM EMG (mV)	-0.269	0.098	-0.095	0.599
RF EMG (mV)	-0.081	0.624	0.098	0.588
VL EMG (mV)	-0.159	0.334	0.079	0.663
EMG Mean (mV)	-0.170	0.300	0.041	0.822
KOOS pain	-0.261	0.113	-0.017	0.928
KOOS Symptoms	**-0.361**	**0.026**	-0.194	0.286
KOOS ADL	-0.101	0.547	-0.067	0.717
KOOS Sport and recreation	-0.043	0.802	-0.070	0.707
KOOS QoL	-0.057	0.736	-0.059	0.749

n, number; PMS, passive motion sense; PPS, passive position sense; APS, active position sense; RFD, rate of force development; ms, milliseconds; mV, millivolt; N.S, newtons per second; RR, rate of relaxation; T1/2PF, time to half peak force; EMD, electromechanical delay; EMG, electromyography; VM, vastus medialis; RF, rectus femoris; VL, vastus lateralis; r, Spearman's correlation statistic; sig; statistical significance, KOOS; knee injury and osteoarthritis outcome score, ADL; activities of daily living, QoL; quality of life. EMD correlations based on n=35.

Significant associations were observed between elasticity values of the distal quadriceps tendon and neuromuscular control measures (Table 3). CS tendon stiffness was significantly negatively associated (moderate) with RFD and $T^{1/2}$PF (*r*= -0.344; *p*=0.032 and *r*= -0.363; *p*=0.023) (Table 3). ER was negatively associated (moderate) with PPS (*r*= -0.441; *p*=0.010) (Table 3). KOOS symptoms was significantly associated with CS values (Table 3). No other significant associations were observed.

Moderate association was observed between PMS and EMD (VL, VM) (*r*=0.420-0.484; *p*<0.013). Muscle strength was positively associated with RR, $T^{1/2}$PF and RFD (25-75% MVC) (*r*>0.515; $p \leq 0.001$, Table 4), but not EMD. There was no association between proprioception and muscle strength. Moderate-strong associations were exhibited between neuromuscular control measures except for EMD (Table 4). KOOS pain was moderately associated with both APS (*r*=0.350 *p*=0.031) and RF EMG (*r*=0.368 *p*=0.023). KOOS Symptoms was moderately associated with APS (*r*=0.400 *p*=0.013) and RF and VL EMG (*r*=0.349 *p*=0.032; *r*= -0.360 *p*=0.026). KOOS ADL was moderately associated with muscle strength (*r*=0.344 *p*=0.043) RF EMG (*r*=0.420 *p*=0.009). Moderate-large association was determined between KOOS sport and recreation and muscle strength (*r*=0.383 *p*=0.025), VM EMG (*r*=0.309 *p*=0.036), RF EMG (*r*=0.403 *p*=0.013) and EMG mean (*r*=0.355 *p*=0.043). KOOS QoL was moderately associated with RF (*r*=0.342 *p*=0.036) and VL EMG (*r*=0.320 *p*=0.05, Table 5).

Table 4. Association between proprioception and neuromuscular control measures.

Variables	PMS		PPS		APS		Muscle Strength		RFD (25-75% MVC)		RR		$T^{1/2}$PF		VM EMD		RF EMD		VL EMD	
	r	sig	*r*	sig	*r*	sig	*r*	sig	*r*	sig	r	sig	*r*	sig	*r*	sig	*r*	sig	*r*	sig
PMS (degrees)	1.000	-	-0.245	0.133	0.132	0.424	-0.082	0.636	-0.254	0.199	-0.094	0.571	-0.293	0.070	**0.484**	**0.004**	0.192	0.278	**0.420**	**0.013**
PPS (degrees)	-0.245	0.133	1.000	-	-0.296	0.068	0.008	0.965	0.205	0.210	0.191	0.245	0.227	0.088	0.013	0.940	0.066	0.709	0.035	0.845
APS (degrees)	0.132	0.424	-0.296	0.068	1.000	-	-0.032	0.854	0.252	0.121	0.122	0.499	0.274	0.091	-0.140	0.431	-0.285	0.102	-0.205	0.245
Muscle strength (Nm.Kg)	-0.082	0.636	0.008	0.965	-0.032	0.854	1.000	-	**0.562**	**0.001**	**0.515**	**0.001**	**0.515**	**0.001**	0.323	0.071	-0.017	0.926	0.143	0.435
RFD (N.S^{-1}) (25-75% MVC)	-0.245	0.119	0.205	0.210	0.252	0.121	**0.562**	**<0.001**	1.000	-	**0.706**	**<0.001**	**0.673**	**<0.001**	-0.046	0.795	-0.230	0.191	-0.143	0.419
RFD (0-25ms)	-0.065	0.693	0.099	0.548	0.269	0.098	**0.367**	**0.028**	**0.488**	**0.002**	**0.504**	**0.001**	**0.488**	**0.002**	0.285	0.102	**0.371**	**0.031**	**0.429**	**0.011**
RFD (25-50ms)	-0.159	0.335	0.218	0.182	0.230	0.159	**0.412**	**0.013**	**0.554**	**0.001**	**0.589**	**<0.001**	**0.570**	**<0.001**	0.192	0.278	0.275	0.155	**0.346**	**0.045**
RFD (50-75ms)	-0.195	0.234	0.222	0.175	0.204	0.213	**0.417**	**0.011**	**0.627**	**<0.001**	**0.577**	**<0.001**	**0.554**	**<0.001**	0.172	0.332	0.269	0.124	0.328	0.058
RFD (75-100ms)	-0.130	0.429	0.243	0.136	0.254	0.119	**0.341**	**0.042**	**0.686**	**<0.001**	**0.515**	**<0.001**	**0.572**	**<0.001**	0.084	0.636	0.121	0.494	0.219	0.214
RFD (0-100ms)	-0.127	0.441	0.108	0.514	0.168	0.308	**0.494**	**0.002**	**0.756**	**0.001**	**0.557**	**<0.001**	**0.416**	**0.009**	0.123	0.490	0.164	0.355	0.246	0.160
RR (ms)	-0.293	0.070	0.191	0.245	0.112	0.499	**0.515**	**0.001**	0.706	**<0.001**	1.000	-	0.811	**<0.001**	-0.155	0.382	-0.206	0.243	-0.155	0.517
$T^{1/2}$PF (ms)	-0.293	0.070	0.277	0.088	0.274	0.091	**0.515**	**0.001**	**0.673**	**<0.001**	**0.811**	**<0.001**	1.000	-	-0.180	0.307	-0.242	0.168	-0.191	0.280
VM EMG (mV)	-0.006	0.969	0.253	0.120	-0.105	0.523	**0.736**	**<0.001**	**0.563**	**<0.001**	**0.389**	**0.014**	**0.464**	**0.003**	**0.518**	**0.002**	0.325	0.061	**0.412**	**0.016**
RF EMG (mV)	0.006	0.971	0.177	0.280	0.003	0.985	**0.731**	**<0.001**	**0.528**	**<0.001**	0.308	0.056	**0.366**	**0.022**	**0.399**	**0.020**	0.233	0.185	**0.397**	**0.020**
VL EMG (mV)	0.208	0.204	0.209	0.202	0.132	0.422	**0.628**	**<0.001**	**0.441**	**0.005**	0.271	0.095	**0.400**	**0.012**	**0.435**	**0.010**	0.251	0.152	**0.397**	**0.020**
EMG mean (mV)	0.144	0.489	0.238	0.145	0.028	0.864	**0.722**	**<0.001**	**0.536**	**<0.001**	**0.344**	**0.032**	**0.432**	**0.006**	**0.486**	**0.004**	0.267	0.127	**0.420**	**0.013**

PMS, passive motion sense; PPS, passive position sense; APS, active position sense; RFD, rate of force development; ms, milliseconds; mV, millivolt; N.S, newtons per second; $^{-}$*MVC, maximum voluntary contraction; %, percentage; RR, rate of relaxation;* $T^{1/2}$PF*, time to half peak force; EMG, electromyography; EMD, electromechanical delay; VM, vastus medialis; RF, rectus femoris; VL, vastus lateralis; EMG, electromyography; VM, vastus medialis; RF, rectus femoris; VL, vastus lateralis; r, Spearman's correlation statistic; sig; statistical significance; EMD data based on n-31-33;* ***bold*** *text indicates p<0.05.*

Table 5. Association between knee injury and osteoarthritis scores, proprioception and neuromuscular control measures.

Variables	KOOS pain		KOOS symptoms		KOOS ADL		KOOS sport & recreation		KOOS QoL	
	r	sig	r	sig	r	sig	r	sig	r	sig
PMS (degrees)	-0.058	0.730	0.021	0.900	-0.069	0.682	-0.127	0.455	0.026	0.875
PPS (degrees)	-0.047	0.780	-0.083	0.619	-0.191	0.250	-0.144	0.395	-0.134	0.421
APS (degrees)	**0.350**	**0.031**	**0.400**	**0.013**	0.309	0.059	0.213	0.206	0.264	0.110
Muscle Strength (Nm.Kg)	0.150	0.389	0.208	0.230	**0.344**	**0.043**	**0.383**	**0.025**	0.313	0.067
RFD (N.S^{-1}) (25-75% MVC)	0.194	0.243	0.110	0.230	0.206	0.214	0.194	0.251	-0.026	0.877
RR (ms)	-0.172	0.301	-0.185	0.267	-0.060	0.722	-0.017	0.922	-0.230	0.165
T1/2PF (ms)	-0.038	0.822	0.056	0.737	0.098	0.557	0.088	0.604	-0.067	0.691
VM EMD (ms)	0.282	0.112	0.168	0.351	0.208	0.224	0.329	0.066	0.276	0.120
RF EMD (ms)	0.119	0.511	-0.051	0.776	0.053	0.771	0.121	0.510	0.056	0.757
VL EMD (ms)	0.058	0.749	-0.026	0.887	0.065	0.721	0.220	0.226	0.080	0.657
VM EMG (mV)	0.286	0.082	0.258	0.117	0.271	0.100	**0.309**	**0.036**	0.208	0.210
RF EMG (mV)	**0.368**	**0.023**	**0.349**	**0.032**	**0.420**	**0.009**	**0.403**	**0.013**	**0.342**	**0.036**
VL EMG (mV)	0.261	0.114	**0.360**	**0.026**	0.294	0.073	0.320	0.054	**0.320**	**0.050**
EMG mean (mV)	0.279	0.090	0.301	0.066	0.306	0.062	**0.335**	**0.043**	0.275	0.095

PMS, passive motion sense; PPS, passive position sense; APS, active position sense; RFD, rate of force development; ms, milliseconds; mV, millivolt; N.S, *newtons per second; MVC, maximum voluntary contraction; %, percentage; RR, rate of relaxation;* T$^{1/2}$PF, *time to half peak force; EMG, electromyography; EMD, electromechanical delay; VM, vastus medialis; RF, rectus femoris; VL, vastus lateralis; EMG, electromyography; VM, vastus medialis; RF, rectus femoris; VL, vastus lateralis; r, Spearman's correlation statistic; sig; statistical significance; EMD data based on n-31-33;* ***bold*** *text indicates p<0.05.*

1.4 Discussion

The quadriceps tendon plays a key role in muscle function, therefore, it may be possible that alterations in tendon elasticity contributes to knee joint impairment. Using SE, an emerging imaging technique, this exploratory study sought to examine the relationships between quadriceps tendon elasticity and neuromuscular control, proprioception and KOOS. Stiffer tendon were found with slower rate of force development, $T^{1/2}$PF, poorer patient reported outcome measures and joint position sense. These findings require further investigation to understand the sequence of events in the pathogenesis of KOA. Specifically, to determine whether the associations seen here are a secondary consequence of pain and/or altered function which may further contribute to disease burden.

Adequate neuromuscular control is essential to enable swift response to perturbation and to reduce the risk of falls associated with the KOA population (Bozbas et al., 2017; Tsonga et al., 2015). In particular, delay in the onset of muscle activity may contribute to the lack of postural control (Takacs et al., 2013). Bojsen-Møller et al., (2005) previously reported that despite recognition that tendon play a vital role in movement and performance, associations between connective tissue and muscle outputs are poorly understood. This study provides new and novel evidence of significant negative association between tendon elasticity and $T^{1/2}$PF. This finding highlights the role of the quadriceps tendon in joint movement and transmission of muscle force subsequent to activation, supporting the associations found in KOA individuals, where increased risk of falls is recognised (Takacs et al., 2013).

Individuals with KOA displayed significant negative association between tendon elasticity and RFD, but not muscle strength. These results support recent KOA study findings by Suzuki et al. (2022) where RFD was significantly reduced without significant muscle strength decline in individuals with severe KOA compared to early KOA. Our findings support earlier proposals and indicate that KOA is related to impaired neuromuscular control (Culvenor et al., 2017; Mau-Moeller et al., 2017) and significantly, that stiffer tendon associated previously in individuals with KOA (Dickson et al., 2022), is associated with a reduction in RFD. An Osteoarthritis Initiative (OAI) population database study determined that higher RFD was significantly associated with decreased risk of worsening self-reported physical function scores (WOMAC evaluated), however not associated with physical function (Hu et al., 2018). Further, RFD is more closely associated with daily activities than maximal muscle strength (Suzuki et al., 2022). The physiological relationship of force transmission through the muscle-tendon unit supports an assumption that tendon characteristics may contribute to the RFD. Additionally, we found KOOS symptoms were associated with increased tendon stiffness. Association between SE tendon stiffness and KOA symptoms is previously unreported and when combined with findings of increased quadriceps tendon stiffness in KOA individuals compared to healthy adult controls (Dickson et al., 2022), highlights an area for future research focus. In particular, detection of tendon stiffness using SE may enable therapeutic management in order to modify mechanic tendon properties to protect against disease progression and aid symptom management.

Extensor muscle impairment in KOA is well documented (Øiestad et al., 2022). Quadriceps muscle function relies on strength and activation, both of which are reduced in individuals with KOA (Alnahdi et al., 2012; Petterson et al., 2008). Accordingly, significant associations between muscle strength, and EMG, and neuromuscular control variables were observed. Similarly, Petterson et al., (2008) found that muscle activation (calculated by central activation ratio) was responsible for 40% of quadriceps muscle strength variance, in individuals with severe KOA. A recent study also observed reduced neuromuscular activation during isometric MVC in individuals with KOA (Mau-Moeller et al., 2017), and further supports the association of these variables.

Baert et al., (2013), demonstrated significantly poorer proprioception, measured by lower limb repositioning error, in individuals with established KOA compared to healthy controls and individuals with early-stage KOA. Furthermore, impaired proprioception may lead to excessive joint movements and instability, contributing to further functional decline (Knoop et al., 2011). Results of this study show that increased tendon stiffness is associated with reduced PPS, whereby alterations in the proprioceptors located in the tendon as a result of pathological changes may explain impaired proprioception. Knoop et al (2011) concluded that the cause of impaired proprioception in KOA is not yet identified. Increased tendon stiffness evidenced in KOA (Dickson et al., 2022) may in some part be responsible, and should be further explored. Additionally, changes in the tendon and potential proprioception may also inhibit the ability to relax the muscles, however we only observed an association between ER and PPS proprioception, and between CS and RFD (25-75% MVC) and $T^{1/2}$PF.

Previous studies have demonstrated tendon elasticity is associated with EMD (Wang et al., 2012), however no association was observed in this study. Grosset et al., (2009), found that following endurance training in young healthy adults that increased tendon stiffness was strongly associated with reduced EMD. Recently, no association was observed between EMD and muscle tendon stiffness of the Achilles tendon (Gago et al., 2019). This study used alternative methods to determine tendon stiffness (torque-angle curve and stiffness index) which may, in addition to the different tendon role, be responsible for conflicting outcomes (Gago et al., 2019).

1.5 Limitations

This study was exploratory in nature, however suffers limitation and vulnerability to error through small sample sizes and lack of generalisability. The results of this study may be subject to type 1 error due to the multiple testing approach employed in this exploratory study, and uncontrolled confounding influences. Further, Strain sonoelastography is not a direct measure of tendon elasticity and estimates tissue elasticity through displacement of tissue from an applied source.

1.6 Conclusions

This exploratory study found significant associations between tendon stiffness and neuromuscular control, and KOOS symptoms scores. Findings are limited to a small population of older adults with confirmed KOA where cause and effect through correlation cannot be established. However, this work provides novel and new evidence to help direct future larger scale studies.

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