



Changes in knee joint angle affect torque steadiness differently in young and older individuals

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ABSTRACT

Purpose: This study investigated the effect of knee joint angle and age on torque steadiness of knee extensors (KE) at varying submaximal isometric contractions.

Methods: 22 young (24.0 ± 2.6 years; 11 women) and 22 older (69.4 ± 2.4 years; 10 women) healthy men and women participated. Maximal voluntary isometric contraction (MVIC) of the KE and flexors was examined at 90° and 60° of knee flexion (0° = full extension). At each angle, participants performed KE isometric contractions (20%, 50% and 80% MVIC) to evaluate torque steadiness, whereas surface EMG was concurrently acquired from the vastus lateralis and biceps femoris muscles.

Results: Age-related impairment in torque steadiness was observed only at 20% MVIC ($p < 0.01$). A lower level of steadiness ($p < 0.001$) with a higher level of agonist and antagonist activations (all $p < 0.01$) was observed at 90° of knee flexion in comparison with contractions at 60°. Young participants were less steady when performing contractions at 90° compared with contractions at 60° of flexion ($p < 0.001$), whereas there was no difference for older participants. Furthermore, a significant effect of agonist activation and antagonist co-activation on torque steadiness was observed, but only in young participants (all $p < 0.05$).

Conclusions: These findings suggest that: (1) knee joint angle affects torque steadiness differently in young and older individuals; (2) an age-related impairment in steadiness was only presented at the lowest considered contraction intensity; and (3) the muscle activation responses were not associated with steadiness in older individuals.

1. Introduction

During the performance of voluntary muscle contractions, the ability to precisely control movements and/or achieve a desired force output (i.e. steadiness) is impaired in older individuals (Enoka et al., 2003; Oomen and van Dieen, 2016). Evaluations of steadiness typically require an individual to exert a constant submaximal force during an isometric contraction of an isolated muscle or a group of muscles at a pre-determined intensity (Enoka et al., 2003; Oomen and van Dieen, 2016). In general, most studies indicate that age-related impairments in force/torque steadiness are most pronounced at low contraction intensities (e.g. < 35% MVIC) in tasks involving various muscle groups, such as the knee extensors (KE) (Tracy and Enoka, 2002), elbow flexors (Bazzucchi et al., 2004) and ankle plantar flexors (Tracy, 2007). On the other hand, other studies have reported that older individuals were less

steady compared to their younger counterparts also during the performance of high-intensity voluntary contractions (e.g. > 70% MVIC) (Burnett et al., 2000; Bazzucchi et al., 2004). Several factors may account for the disparities in outcomes observed between studies, such as the muscle group tested (Bazzucchi et al., 2004; Tracy, 2007) and the type of contraction performed (e.g. isometric & anisometric) (Tracy and Enoka, 2002). Another integral factor influencing torque steadiness is the joint angular position. As an example, in young individuals performing sustained submaximal KE contractions, a lower level of torque steadiness with higher levels of agonist activation and antagonist co-activation (measured by surface EMG) has been reported at a more flexed knee joint angle compared to a more extended angle (Krishnan et al., 2011). This phenomenon is likely the consequence of the variations in the mechanical advantage of moment arm (Kellis and Baltzopoulos, 1999) and in the level of afferent feedback originating

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from the biological structures in the muscles and the joints (Bigland-Ritchie et al., 1992; Becker and Awiszus, 2001). Torque steadiness has been shown to be modulated by alternating agonist activation and antagonist co-activation (Baudry et al., 2010), but it is still largely unknown how the knee joint angle-induced differences in neuromuscular responses influence the torque steadiness in young and older individuals. In the present study, therefore, we examined KE torque steadiness in young and older individuals, whilst simultaneously considering mechanical and neuromuscular factors that are known to affect steadiness. As a primary objective, we investigated the effect of knee joint angle on torque steadiness at varying KE contraction intensities in young and older individuals. As a secondary objective, we sought to explore the effect of activations of agonist (i.e. quadriceps) and antagonist (i.e. hamstrings) muscles on torque steadiness. We hypothesized that: (1) isometric KE contractions performed at a more knee-extended joint angle would be steadier than at a more flexed angle in both young and older individuals; (2) the effect of changing knee joint angle on steadiness would be more pronounced in younger than in older individuals; (3) the reduction in torque steadiness with advancing age would be due to the alterations in activations of the agonist and antagonist muscles.

2. Materials and methods

2.1. Participants

Twenty-two young (11 men and 11 women) and twenty-two older (12 men and 10 women) healthy individuals volunteered to participate. The general characteristics of the participants are detailed in Table 1. All participants were deemed 'medically stable'; this was established using a specific medical history questionnaire (Greig et al., 1994). Briefly, participants were free from previous lower limb surgery and any cardiovascular, cerebrovascular, neurological, uncontrolled metabolic, respiratory and major systemic diseases. Moreover, none of the participants had performed strength training or engaged in competitive sports within the last five years. The University Human Research Ethics Committee approved the study protocol. All participants provided written informed consent prior to the study in accordance with the Declaration of Helsinki.

2.2. Experimental procedures

After familiarization with the testing procedures, each participant attended two laboratory test sessions separated by at least three days. In each test session, after a 5-minute warm-up performed on a cycle ergometer at 70–80 rpm with light resistance (50–100 W), participants were requested to perform the following tasks on an isokinetic dynamometer at one of two pre-determined knee joint angles (90° or 60°; the adopted knee joint angular position for each laboratory testing session was randomized adopting a counterbalanced procedure): (1) MVIC of the KE; (2) MVIC of the knee flexors (KF) and (3) three sustained submaximal KE isometric contractions corresponding to 20%, 50% and 80% MVIC.

MVIC Task. After a warm-up and familiarisation with the testing procedures, each participant performed a minimum of three maximal

knee extension and flexion contractions; a 3-minute rest followed each contraction. At each attempt, participants were asked to generate force 'as strong and as quick as possible' for approximately 3–4 s, while on-line visual feedback, set at the best attempt of each participant, was provided (except for the first attempt). Participants were instructed to replicate their performance displayed on the computer monitor and were verbally encouraged to exceed the target line. The greatest KE and KF torques attained by each participant were chosen as the MVIC torque and used to normalize the muscle activity during the submaximal torque steadiness tasks.

Torque-steadiness task. After assessing the MVIC, participants then performed submaximal isometric contractions of the KE at three pre-determined contraction intensities, i.e. 20%, 50% and 80% MVIC. The order of contraction intensity was randomised to minimize the potential effect of fatigue and skill acquisition. A horizontal target torque band with a width corresponding to $\pm 5\%$ of the target torque value was displayed on the computer monitor placed at 1.5 m distance from the participants. The participants were asked to match the target torque and maintain it 'as steady as possible' for approximately 12 s, while verbal encouragement and instruction were provided (Tracy and Enoka, 2002). Each sustained contraction was followed by a resting period of either 5-minutes (for the 20% and the 50% MVIC) or 10-minutes (for the 80% MVIC).

2.3. Mechanical recordings

Knee extension and flexion isometric torque of participants' dominant (self-reported) lower limb were quantified with an isokinetic dynamometer (Biodex III, Biodex Medical Systems, Shirley, NY, USA). Participants were seated comfortably on the dynamometer chair and were firmly stabilized by torso, pelvis and thigh straps. The hip joint was fixed at 80° measured by a goniometer with the arms aligned to the lateral midline of pelvis and femoral lateral epicondyle, whilst the knee joint was set at two different angles (i.e. 90° or 60°, where 0° represents full knee joint extension). The lower leg was strapped to the lever arm of the dynamometer about 2 cm above the lateral malleolus, and the centre of rotation of the lever arm was aligned with the lateral femoral condyle. The torque trace was displayed on a computer monitor to provide participants with visual feedback, and torque signals were amplified with a gain of 1000, sampled at 512 Hz, and stored on a PC using a 16-bit A/D converter data acquisition system (Biopac System, Inc., Goleta, CA, USA).

2.4. Surface EMG recording

Surface EMG signals were recorded from the vastus lateralis (VL) and long head of the biceps femoris (BF) muscles of the right leg to represent the activity of the quadriceps and hamstring muscle groups, respectively (De Vito et al., 2003). Two Ag/AgCl bipolar surface electrodes (Blue Sensor N-00-S, Ambu Medcotest A/S, Ølstykke, Denmark) were placed 20 mm apart (centre-to-centre) on the skin above the belly of the muscle (shaved, lightly abraded and cleaned with ethyl alcohol) according to the SENIAM guidelines (Hermens et al., 1999). An additional ground electrode was placed over the patella. Surface EMG signals were amplified with a gain of 1000, sampled at 2048 Hz, and then

Table 1
Participants characteristics.

	n	Age (year)	Stature (m)	Body Mass (kg)	BMI (kg/m ²)
Young Men	11	24.2 ± 2.0	1.82 ± 0.06	79.0 ± 16.2	23.6 ± 3.7
Young Women	11	23.8 ± 2.4	1.66 ± 0.06	63.1 ± 11.1	23.0 ± 4.2
Older Men	12	70.2 ± 1.9	1.79 ± 0.04	84.1 ± 9.8	26.3 ± 2.7
Older Women	10	68.4 ± 2.7	1.63 ± 0.05	64.8 ± 7.8	24.6 ± 3.3

Values are mean ± SD. n = number of participants

stored on the aforementioned PC using the same data acquisition system. In addition, maps on transparency films were utilizing skin marks (e.g. freckles or scars) and/or anatomical reference points (e.g. the border of patella) were used to ensure that same recording location was used during the second laboratory test session.

2.5. Subcutaneous adipose tissue thickness

The subcutaneous adipose tissue thickness covering the VL and BF muscles was measured via using a B-mode real-time ultrasound imaging unit (DP-6600, Mindray Bio-Medical Electronics CO., LTD, Shenzhen, China) equipped with a 40-mm, 7.5-MHz linear-array probe to evaluate the potential influence it could have on the surface EMG recordings. As described previously (Wu et al., 2016), images were taken at the position where the EMG electrodes were placed from VL and BF muscles with the participants in a supine and prone position, respectively. The average value of the best quality image from each muscle was assessed using computer software (AutoCAD 2017; Autodesk, Inc., San Rafael, CA) for future analysis.

2.6. Data analysis

Data recorded were processed using custom-written programs (MATLAB R2017a, MathWorks, Natick, MA, USA). Surface EMG signals were bandpass filtered between 20 and 500 Hz using a fourth-order zero-phase Butterworth filter. For the MVIC tasks, the maximal KE and KF torque was estimated via a 1-second window corresponding to the highest average within any single torque recording. For the torque steadiness task, the middle of the 8-second was selected to avoid the transient phase (Bazzucchi et al., 2004). The mean and coefficient of variation (CV) of the torque were determined. The CV of the torque was expressed as a percentage of the mean torque exerted [i.e. standard deviation (SD)/mean torque × 100%] and represented the torque steadiness as it allows an appropriate comparison of the torque steadiness between different populations regardless of absolute differences in muscle strength.

To quantify the agonist EMG time and frequency components during the knee extension MVIC and steadiness tasks, the root mean square (RMS) and median frequency (MDF) were calculated over a period of 1-second corresponding to the MVIC of the highest torque obtained and over the middle 4-second epoch of the submaximal contractions used for torque steadiness (i.e. CV) analysis. To assess the level of agonist (i.e. quadriceps) activation during the torque steadiness task, the VL RMS (EMG amplitude) values recorded during each of the contraction intensities were normalized with respect to the VL RMS values obtained during the MVIC of the KE at the same joint angle. To assess the level of antagonist (i.e. hamstrings) co-activation, the BF RMS (EMG amplitude) values recorded at each contraction identity were normalized with respect to BF RMS obtained during the MVIC of the KF at the same joint angle (Wu et al. 2017). The MDF of the EMG recordings from the VL muscle was estimated using fast Fourier transform calculated with Hanning windows of 1000-ms duration and 75% overlap.

Table 2
Effects of age and knee joint angle on knee extension and flexion MVIC.

MVIC (Nm)	Young		Older		Main effect				Interaction effect
					Age		Joint angle		Age × angle
	90°	60°	90°	60°	Diff%	p value	Diff%	p value	p value
KE	189.9 ± 70.9	206.8 ± 67.1	141.9 ± 44.6	146.7 ± 46.8	27.2	< 0.01	-6.6	< 0.05	0.183
KF	83.8 ± 36.3	103.8 ± 39.8	55.4 ± 16.6	71.2 ± 22.2	32.5	< 0.01	-20.5	< 0.001	0.374

Values are mean ± SD. KE = knee extensors, KF = knee flexors

2.7. Statistical analysis

An analysis of variance (ANOVA) with repeated-measures was adopted to compare the dependent variable of MVIC on knee joint angle for both KE and KF. A three-way ANOVA with repeated measures was performed on torque steadiness (i.e. CV), agonist activation, antagonist co-activation and MDF, with the objective of testing for differences during submaximal isometric contractions. Moreover, a repeated-measures ANCOVA was also performed adopting subcutaneous adipose tissue thickness covering the VL and BF muscle as a covariate on agonist activation and antagonist co-activation, respectively. A Greenhouse-Geisser correction was employed when the assumption of sphericity was violated. When a significant interaction was revealed, pairwise comparisons were performed with Bonferroni adjustment. A linear mixed-model analysis was performed to estimate the effect of agonist activation and antagonist co-activation (i.e. predictor) on torque steadiness (i.e. dependent variable), respectively. The residual of the model did not violate the normality of residuals assumption tested by a Shapiro-Wilks test. Statistical analysis was performed using SPSS 24.0 (IBM Ireland Ltd., Dublin, Ireland). Statistical significance was set at $p < 0.05$.

3. Results

No interaction effects between age and sex were observed on any of the measures of MVIC, torque steadiness (CV), and EMG responses during the isometric contractions. Therefore, to be consistent with the objectives of our study, for the subsequent analyses, the results were collapsed across sex for both the young and older participants.

3.1. MVIC

As expected, young participants were ~27% and ~33% stronger than older participants during maximal KE ($F_{(1, 42)} = 10.0$; $p < 0.01$) and KF ($F_{(1, 42)} = 12.0$; $p < 0.01$) voluntary contraction. Furthermore, both maximal KE ($F_{(1, 42)} = 6.1$; $p < 0.05$) and KF ($F_{(1, 42)} = 56.4$; $p < 0.001$) strength were greater at 60° than at 90° of knee flexion (Table 2).

3.2. Torque steadiness

A joint angle effect was revealed ($p < 0.001$), irrespective of age, with a lesser steadiness being observed at 90° than at 60° of knee flexion. Moreover, an age by joint angle interaction ($F_{(1, 42)} = 10.0$; $p < 0.01$) showed that, regardless of contraction intensity, the isometric contractions performed at 60° were steadier than those performed at 90° of knee flexion, but only in young participants ($p < 0.001$) (Fig. 1a). In addition, there was an interaction effect between age and contraction intensity ($F_{(1.79, 83.5)} = 7.5$; $p < 0.01$), showing that older participants were less steady than their younger counterparts, but only at 20% MVIC ($p < 0.01$; Fig. 2).

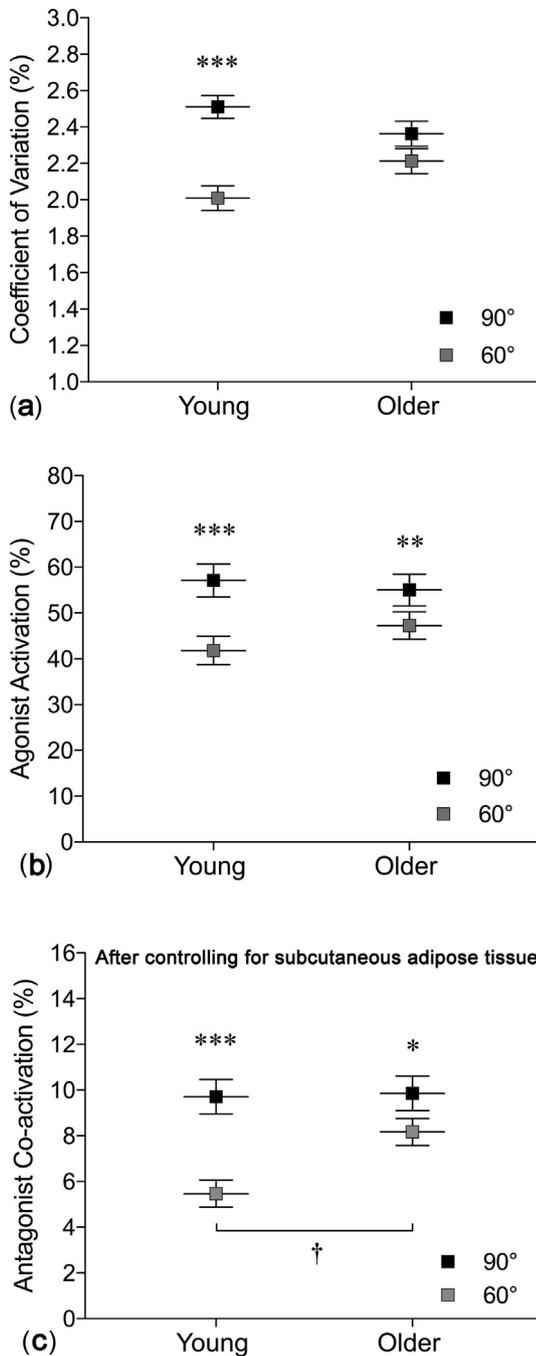


Fig. 1. Torque steadiness (i.e. coefficient of variation) (a), agonist activation (b) and antagonist co-activation (c) at 90° and 60° of knee flexion in young and older participants. Values are means \pm SEM. * $p < 0.025$, ** $p < 0.01$, *** $p < 0.001$ for 90° compared with 60° of knee flexion; † $p < 0.001$ for young compared with older participants.

3.3. Surface EMG

A joint angle by contraction intensity interaction was observed, irrespective of age, for the agonist activation ($F_{(1.3, 55.1)} = 10.5$; $p < 0.01$), antagonist co-activation ($F_{(1.4, 57.9)} = 17.8$; $p < 0.001$) and MDF ($F_{(1.9, 80.7)} = 9.3$; $p < 0.001$), with a difference noted between 90° and 60° of knee flexion at all contraction intensities (all $p < 0.01$; Fig. 3). Moreover, young participants were characterized by a greater difference in agonist activation between joint angles when compared to their older counterparts ($F_{(1, 42)} = 5.4$, $p < 0.05$; Fig. 1b). Nevertheless, no differences in antagonist coactivation were

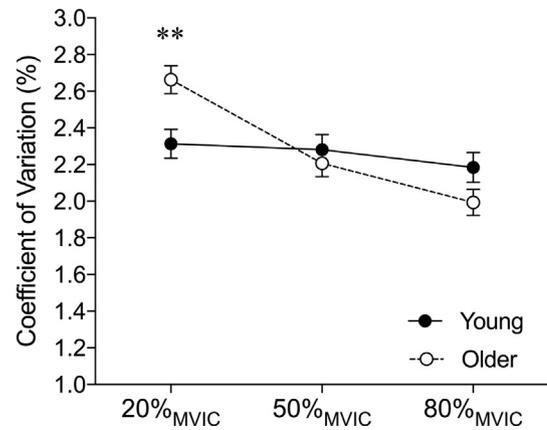


Fig. 2. Torque steadiness (coefficient of variation) during submaximal isometric contractions (i.e. 20%, 50% and 80% MVIC) in young and older groups. Values are means \pm SEM. ** $p < 0.01$ for young compared with older participants.

observed in young and older at the two joint positions, only the young participants exhibited a greater antagonist co-activation at 90° with respect to 60° of knee flexion ($p < 0.001$). However, when the subcutaneous adipose tissue covering BF was considered as a covariate ($F_{(1, 41)} = 19.3$; $p < 0.001$), a greater difference between joint angles was also observed ($F_{(1, 41)} = 6.6$; $p < 0.05$), showing that, in both age groups, isometric contractions at 90° of knee flexion were associated to a higher level of antagonist co-activation in comparison with contractions performed at 60° (all $p < 0.025$); and the level of antagonist co-activation was higher in the older than the younger participants at 60° of knee flexion ($p < 0.01$; Fig. 1c). Whereas, the ANCOVA analysis performed adopting subcutaneous adipose tissue covering the VL as a co-variate was not significant.

3.4. Effect of muscle activations on torque steadiness

The linear mixed model analysis showed that both agonist activation (interaction effect: $F = 13.9$; $p < 0.001$) and antagonist co-activation (interaction effect: $F = 16.6$; $p < 0.001$) had different effects in young and older participants. In fact, increased levels of agonist activation ($coefficient = 0.008$; $p < 0.05$) and antagonist co-activation ($coefficient = 0.031$; $p < 0.01$) were associated with a decreased torque steadiness, but only in young participants.

4. Discussion

In the present study, for the first time, the effect of knee joint angle on torque steadiness was investigated across a range of submaximal isometric contractions (i.e. 20%, 50% and 80% MVIC) in young and older healthy individuals. Moreover, the agonist-antagonist muscle activation (EMG RMS amplitude) was specifically considered to investigate the potential influence it could have on the torque steadiness. The main findings were that (1) regardless of knee joint angle, older participants were less steady than their younger counterparts, but only at the lowest evaluated contraction intensity (i.e. 20% MVIC in the present study) (Fig. 2); (2) when the effect of the joint angle was compared between the two age groups, a greater difference in terms of steadiness and muscle activations was observed in young compared to older participants (Fig. 1); and (3) an enhanced antagonist co-activation did not influence torque steadiness in older individuals.

Not surprisingly, an age-related loss of maximal isometric torque was observed during knee extension and flexion in the older participants, which is consistent with the observations of several previous studies (Lindle et al., 1997; Ditroilo et al., 2010; Wu et al., 2016 among the others). It is well established that MVIC of the KE and KF is

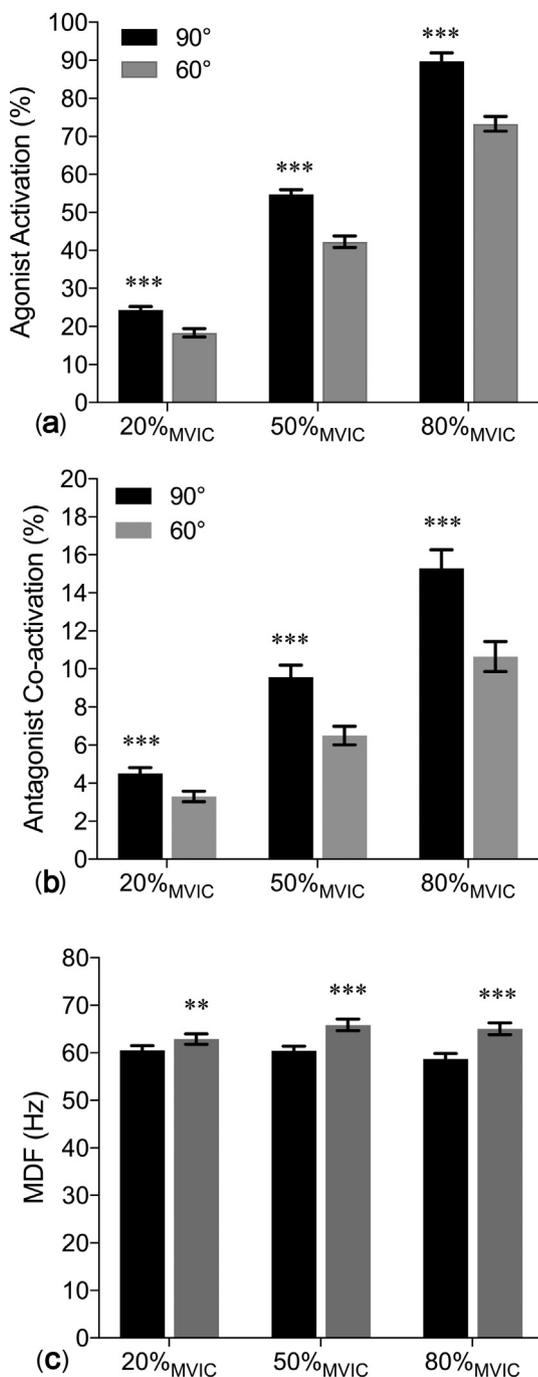


Fig. 3. Agonist activation (a), antagonist co-activation (b) and MDF (b) during submaximal isometric contractions (i.e. 20%, 50% and 80% MVIC) performed at 90° (black) and 60° (grey) of knee flexion. Values are means \pm SEM. ** $p < 0.01$, *** $p < 0.001$ for 90° compared with 60° of knee flexion.

dependent on the joint angle, with lower MVIC often observed when the knee angular position is close to full extension and/or flexion (Becker and Awiszus, 2001; Kubo et al., 2004). Indeed, in the present study, a smaller MVIC was recorded at 90° than at 60° of knee flexion for both KE and KF across both age groups.

4.1. Effect of knee joint angle on torque steadiness

Similar to the observations of previous studies examining either the ankle dorsiflexors (Bigland-Ritchie et al., 1992) or knee extensors (Krishnan et al., 2011), we observed that KE was steadier at 60° than at

90° of knee flexion. The torque steadiness dependence on the joint angle could be explained, at least in part, by the mechanical disadvantage due to the lengthened quadriceps muscles at 90° compared to 60° of knee flexion, likely because of an increase in the number of active cross-bridge and a rise in internal force (Ng et al., 1994; Place et al., 2005). In addition, during isometric contractions, KE torque steadiness can also be influenced by the modulation of voluntary agonist activation and antagonist co-activation in response to the changes in knee joint angular position (Yoshitake et al., 2007; Krishnan et al., 2011). For instance, the isometric contractions performed at 90° of knee flexion have shown a decrease in torque steadiness and an increase in EMG activity of both agonist and antagonist muscles with a concomitant decrease in the MDF of the EMG power spectrum when compared with contractions at 30° of knee flexion (Krishnan et al., 2011).

We observed a similar pattern, regardless of age, with a higher level of agonist (i.e. quadriceps) activation (Fig. 3a) and antagonist (i.e. hamstrings) co-activation (Fig. 3b), but a lower level of MDF (Fig. 3c) at 90° compared to 60° of knee flexion across all contraction intensities. It has been suggested that neural drive is enhanced during stretching of a muscle, hereby the response of the muscle spindles results in greater Ia afferent excitatory input into the α motor neuron pools of the quadriceps (Becker and Awiszus, 2001; Kubo et al., 2004). In turn, the reduction in the MDF of the EMG power spectrum could be also explained by the increase in muscle length (i.e. 90° of knee flexion), as a lengthened muscle would result in a decrease in muscle fibre diameter with a consequent slowing of muscle fibre conduction velocity (MFCV) (Arendt-Nielsen et al., 1992). In particular, under the same electrodes, the volume of the individual muscle fibre does not alter with the lengthening of the muscle (Inbar et al., 1987), but results in wider recorded muscle fibre action potentials with a prolonged duration of the compound action potentials (due to \downarrow MFCV), and consequently an increased power in the lower portion of EMG power spectrum (\downarrow MDF) (Arendt-Nielsen et al., 1992). Moreover, variations in subcutaneous tissue properties and the distance between the muscle fibres and electrodes may change across different populations, which would also affect EMG responses in both time and frequency domains. Indeed, in the present study, we observed a significant effect for adipose tissue covering BF muscle, when it was included as a covariate, showing a higher level of co-activation in older than young participants at 60° of knee flexion. This confirms our previous observations from our laboratory (Wu et al., 2017) and suggests that the effect of subcutaneous adipose tissue should be considered to minimize the potential influence of cross-talk contamination among neighbouring muscles when the surface EMG amplitude is adopted to measure muscle activations across different populations (Solomonow et al., 1994). On the other hand, changes in tissue properties leading to an increase in EMG amplitude would typically be associated with an increased MDF (Lowery et al., 2002), suggesting that additional factors contribute to the increase in EMG amplitude and decrease in MDF with increasing muscle length which we observed.

4.2. Effect of age on torque steadiness

In the present study, we observed that torque steadiness was more variable at 90° when compared to 60° of knee flexion in young but not in older participants. This result conflicts with one of our study hypothesis on older individuals, but is in line with a previous study focusing on young individuals (Krishnan et al., 2011). This age-related difference on steadiness in response to the variation in knee joint angular position could be partly attributed to an impairment in the spindle sensitivity (Corden and Lippold, 1996) and enhanced musculotendinous compliance (Narici and Maganaris, 2007) usually observed with aging. At more knee-flexed positions (i.e. longer quadriceps muscle length), the patellar tendon absorbs a larger part of the stretch imposed on the muscle-tendon unit (Rack et al., 1983). However, in older individuals, the more compliant muscle-tendon complex will

transmit less stretch to the muscle spindles thus dampening the Ia afferent input to the α motor neuron pool resulting from an increase in muscle length (Kluka et al., 2015). Accordingly, we observed a smaller increase in the agonist activation and antagonist co-activation in older compared with their younger counterparts when lengthening the muscle (i.e. from 60° to 90° of knee flexion). Therefore, it suggests that mechanical advantage would be lesser effective in older individuals when performing steadiness tasks, probably due to a 'slack' tendon transmitting force from muscle at the optimal compared to other angular positions (e.g. 60° vs 90° of knee flexion in the present study).

It has been proposed that, at least for voluntary knee extension contractions, the older individuals tend to use an enhanced antagonist (i.e. hamstrings) co-activation to reduce movement variability (Seidler-Dobrin et al., 1998) and maintain the stability of the joint (Hortobagyi and Devita, 2006; Latash, 2018). However, in the present study, the age-related reduction in quadriceps torque steadiness does not appear to be caused by an enhanced level of antagonist co-activation, although a higher level of antagonist co-activation was observed in older participants at 60° of knee flexion. Consistent with our observation, Burnett et al. (2000) reported that the impaired steadiness exhibited by older individuals was not associated with co-activation of the antagonist muscle. Moreover, this observation has been further corroborated by the results of strength training studies showing an improvement in torque steadiness accompanied by an unchanged co-activation in healthy older individuals (Laidlaw et al., 1999; Tracy et al., 2004). On the other hand, in keeping with previous studies (Tracy and Enoka, 2002; Dewhurst et al., 2007; Tracy, 2007), we confirmed that older participants were less steady than young participants, whilst performing KE contraction at the lowest contraction intensity assessed (i.e. 20% MVIC) (Fig. 1), and this observation was not influenced by altering knee joint angle. Given that there are distinct contributions of neurophysiological mechanisms in force production and movement control, the observed age-related reduction in torque steadiness only at lowest contraction intensity could be attributed to the various neuromuscular features related to the modulation of MU activity with aging (Enoka et al., 2003; Farina and Negro, 2015). For instance, a previous simulation study has demonstrated an association between torque steadiness and motor unit (MU) synchronization (Yao et al., 2000). Furthermore, Castronovo et al. (2018) recently reported that the declined force steadiness observed with aging could be related to an augment in common input fluctuations at low frequencies during isometric contractions of tibialis anterior muscle performed at 20% MVIC. Thus, it is possible to speculate that, in the present study, the reduced steadiness observed at 20% MVIC in older participants could be the consequence of changes in the common synaptic input to motor neurons caused by the MU remodelling as well as the age-related increase in synaptic noise and possible neuro-degenerative processes influencing the corticospinal tract (Lexell, 1997; Erim et al., 1999; Enoka et al., 2003).

A limitation of the present study was that we only used bipolar surface EMG measurements to examine muscle activity. Although this technique has been widely used *in vivo* to examine the potential neuromuscular alterations and/or difference in diverse populations (Macaluso et al., 2002; Tracy and Enoka, 2002; Hunter et al., 2004 among the others). Therefore, we acknowledge that interference EMG signals can only provide a more 'global' view on the EMG responses in the time and frequency domains, and hence do not necessarily truly reflect MU recruitment strategies and individual MU properties (Keenan et al., 2006; Del Vecchio et al., 2017), or information regarding the modulation of the common synaptic input to neurons (Farina et al., 2002; Farina et al., 2004). As such, future studies should adopt new techniques, such as high-density surface EMG, to gain a better insight into MU behaviour and neural modulation *in vivo* (Farina et al., 2016; Del Vecchio et al., 2017).

In summary, the results of the present study showed that the knee joint angle affects torque steadiness differently in young and older individuals, with a greater torque steadiness being observed at 60° when

compared to 90° of knee flexion, but only in young participants. In addition, our results confirmed that, regardless of knee joint angular position, older individuals were less steady when performing isometric contractions at the lowest intensity (i.e. 20% MVIC in the present study). These age-related differences in torque steadiness were not affected by alternating activations of agonist and antagonist muscles.

Declaration of Competing Interest

The authors have no conflicts of interest to declare

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