Planar flexor strength at different knee positions in older and young males and females

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ABSTRACT

Introduction: This study examined the effects of age and knee position (fully extended, K0; 90° flexed, K90) on plantar flexor maximal voluntary contraction (MVC) torque and the rate of torque development (RTD) in both sexes.

Methods: The following parameters were measured in 32 older (66–81 yr, 17 males and 15 females) and 37 young (20–30 yr, 18 males and 19 females) adults: evoked peak twitch torque, time to peak twitch torque, RTD of the twitch torque, MVC torque, RTD at early (0–50 ms, RTD0–50) and later (100–200 ms, RTD100–200) time intervals during explosive contractions, voluntary activation (VA%) during MVC, root mean square of the electromyogram (RMS-EMG) during MVC and explosive contractions, thickness of the triceps surae, and pennation angle of the medial gastrocnemius. The magnitudes of the differences were interpreted based on Cohen’s d (d).

Results: Age-related difference in RTD0–50 was greater for females (d = 1.36) than males (d = 1.03) and vice versa for MVC torque and RTD0–200. For young adults, MVC torque, RTDs, and RMS-EMGs of the gastrocnemius but not the soleus were significantly higher in K0 than in K90. For older adults, no differences in voluntary RTDs were observed between K0 and K90, and RMS-EMGs of the gastrocnemius were higher in K90 than in K0, except for that of the lateral gastrocnemius in the early time intervals during explosive contraction. The age-related difference in the effect of knee position for RTD0–50 was higher in females than males, and vice versa for MVC torque and RTD100–200.

Conclusion: The results suggested that the effects of age and knee joint angle on the plantar flexor performance were more prominent in the early phase of force production for females and were more apparent in the later phase and maximal force for males.

1. Introduction

The maximal and rapid force-generating capabilities of the plantar flexors are attenuated with aging (Dalton et al. 2016; Thompson et al. 2014) and are associated with functional performance during human movement in older adults (Clark et al. 2013; Ema et al. 2016; Melzer et al. 2009). For example, the plantar flexor peak force/torque of maximal voluntary isometric contraction (MVC) (Melzer et al. 2009) and the rate of force/torque development (RFD/RTD) (Ema et al. 2016), which is defined as the slope of the time force/torque curve during the initial phase of isometric contraction from a low or resting level (Aagaard et al. 2002), were related to postural stability. Older adults who reported falling exhibited lower MVC torque (Cattagni et al. 2014) and RTD (LaRoche et al. 2010) during planter flexion compared to those who did not fall. Therefore, understanding the factors that contribute to age-related reductions in the maximal and explosive plantar flexor performance is critical to prevent functional disability in older adults.

Perspective of sex difference is expected to be useful for understanding the underpinning mechanisms of age-related attenuation of the plantar flexor performance. It is unclear whether the sex-specificity exists in the age-related differences in the performance. Plantar flexion strength is mainly generated by the triceps surae (Fukunaga et al. 1992). The medial and lateral gastrocnemius (MG and LG) consist of approximately 50% of fast twitch fibers while the soleus (SOL) contains <15% of fast twitch fibers (Johnson et al. 1973). Age-related atrophy is more likely to occur in fast than in slow twitch fibers (Lexell et al. 1988),
and males generally have more fast twitch fibers than females (Hunter 2014). Consistent with these findings, MG and LG but not SOL physiological cross-sectional areas were smaller in older males (OM) than young males (YM) (Morse et al., 2005), and age-related atrophy of MG began at earlier ages in OM than in older females (OF) (Fujitohera et al., 2010). Even during explosive force production, the size principle of motor unit recruitment is maintained (Duchateau and Enoka 2011), implying that the effect of preferential age-related atrophy of fast twitch fibers and of gastrocnemius would be more apparent in the later than early phase of force production. It is possible that the effect of age on the neuromuscular performance during plantar flexion is more evident in males than in females, especially at later phases of explosive contractions and maximal torque. This should be investigated experimentally considering that training-induced improvement of RTD and neuromuscular adaptations in older adults were phase dependent and specific to muscles among the triceps surae (Ema et al. 2017).

Plantar flexor performance is affected by knee joint position. Previous studies (Cresswell et al. 1995; Dalton et al. 2013; Hali et al. 2019; Kennedy and Cresswell 2001; Wakahara et al. 2007) demonstrated that the plantar flexor MVC force/torque is attenuated by knee flexion in YM. The smaller MVC strength in a flexed knee compared to an extended knee can be attributed to neuromuscular factors such as lower length-dependent force-generating capacity (Wakahara et al. 2007) and inhibited neuromuscular activation (Hali et al. 2019) of the biarticular gastrocnemius at the flexed knee joint angle. If age-related neuromuscular changes are specific among the triceps surae and between males and females, knee joint position can affect the plantar flexion strength differently between ages and sexes. However, this has not been substantiated by previous studies. When plantar flexion torque is required during human movements, knee joint is not always fully extended. In addition, the specificity of joint angle in the training effect can be induced (Kiti and Sale 1989). Thus, evidence of the plantar flexor performance is different between ages and sexes (Table 1), assessed using a previously validated questionnaire (Craig et al. 2003). We did not control the menstrual cycle for YF due to variability in the cycles of the participants appears to have had minimal effect on the current results. All participants visited our laboratory twice for the experiments: the first visit was for familiarization and the second visit was for experimental testing within 1 week from the first visit. During the familiarization session, the participants practiced maximal and explosive voluntary plantar flexion under the experimental setting. This should be investigated experimentally considering that training-induced improvement of RTD and neuromuscular adaptations in older adults were phase dependent and specific to muscles among the triceps surae (Ema et al. 2017).

Data are shown as mean ± standard deviation. *Indicates a significant difference between ages in each sex. †Denotes a significant difference between sexes in each age. ¥Shows a significant difference between fully extended (K0) and 90° flexed (K90) knee positions. LG, lateral gastrocnemius; MET, metabolic equivalent; MG, medial gastrocnemius; SOL, soleus.

2.2. Procedures

All procedures were conducted with the right knee in two positions (Fig. 1) unless otherwise noted: fully extended (K0) and 90° flexed (K90) (Ema et al., 2018b; Kennedy and Cresswell 2001). Participants lay prone on the bench of a dynamometer (CON-TREX MJ, PHYSIOMED, Germany) and were secured at the body to the dynamometer with non-elastic straps. In K90, a heavy block was placed in front of the thigh to prevent knee joint movements, in reference to a previously published figure (Wakahara et al. 2009). The ankle joint angle was kept in the anatomical position. Dependent variables were obtained in the following order: muscle architecture, triceps surae twitch responses, MVC torque, VA% during MVC, and RTD during explosive contractions,

![Diagram](image-url)

**Fig. 1.** Schematic illustration of the experimental setup at extended (K0) and 90° flexed knee positions (K90).

| Table 1 | Physical characteristics, physical activity, and muscle architecture of participants. |
|---------|---------------------------------------------------------------------------------|
|         | **Older males (n = 17)** | **Older females (n = 15)** | **Young males (n = 18)** | **Young females (n = 19)** |
| Age Years | 74 ± 5* | 72 ± 4* | 22 ± 2 | 22 ± 1 |
| Height cm | 164.3 ± 6.2 | 154.4 ± 4.6 | 170.6 ± 5.0 | 157.1 ± 4.0 |
| Body mass kg | 76.7 ± 10.3 | 55.5 ± 6.0 | 62.8 ± 5.4 | 50.9 ± 5.6 |
| Body mass kg.m⁻² | 25.1 ± 3.8 | 23.3 ± 2.5 | 21.5 ± 2.0 | 20.6 ± 2.0 |
| Physical activity min⁻¹ | 5315 ± 3.9 | 4574 ± 3.8 | 3115 ± 2.9 | 2583 ± 2.6 |
| Muscle thickness | 4.5 ± 0.7* | 3.4 ± 0.8 | 3.6 ± 0.6 | 3.8 ± 0.7 |
| PEN | 4.3 ± 0.8 | 3.7 ± 0.8 | 3.8 ± 0.5 | 3.8 ± 0.8 |

### 2.2. Procedures

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with random order between K0 and K90. During testing, the centers of the ankle joint and dynamometer were carefully aligned. All analyses were performed with Labchart software (version 8, ADInstruments, Australia).

2.3. Electromyography (EMG)

Surface EMG signals were recorded from the MG, LG, SOL and tibialis anterior (TA) using bipolar Ag/AgCl electrodes (Blue Sensor N-00-S, Ambu A/S, Denmark) with a 20 mm center-to-center distance of the electrodes. The EMG signals were amplified (gain = 1000) with a bio-amplifier system (MEG-6108, Nihon Koden, Japan). Using real-time B-mode ultrasonography (ACUSON S2000, Siemens Medical Solutions, USA), the muscle belly and fascicle longitudinal directions were confirmed. Electrodes were placed at 30–40% of the lower leg length from the popliteal crease to the lateral malleolus for MG, LG, and TA after the skin was shaved,rubbed with sandpaper and cleaned with alcohol. For SOL, the placement was ~5 cm distal from the level of the 40% of the lower-leg length at which superficial region of SOL was visualized (Ema et al., 2017). The ground electrode was placed over the left lateral malleolus. The EMG and torque data were obtained simultaneously at 4 kHz using an A/D converter (PowereLab16/35, ADInstruments, Australia). The EMG data were band-pass filtered between 6 and 500 Hz, but EMG onset was detected from non-filtering EMG signals (Ema et al., 2018a).

2.4. Evoked responses

The triceps surae responses at rest (peak twitch torque and peak-to-peak amplitude of compound motor action potential $[M_{\text{max}}]$ and H-reflex $[H_{\text{max}}]$ of MG, LG, and SOL) were evoked by stimulation of the tibial nerve in the popliteal fossa with a Ag/AgCl cathode ($2 \times 2$ cm). An Ag/AgCl anode ($4 \times 5$ cm) was placed over the ventral aspect of the thigh. Rectangular pulses with durations of 1 ms were delivered using a constant-current variable voltage stimulator (DS7A, Digitimer Ltd., UK). The supramaximal stimulus intensity for each knee joint was determined by increasing the current intensity until the twitch torque and $M_{\text{max}}$ reached a plateau. Five supramaximal twitch and $M_{\text{max}}$ were obtained at a higher current ($>20\%$) every 10 s. The peak twitch torque, time-to-peak torque (TPT), RTD of the twitch torque ($\text{RTD}_{\text{twitch}}$), which was calculated as the peak twitch torque divided by TPT, and $M_{\text{max}}$ were determined and averaged across the five twitches. The torque data were low-pass filtered at 500 Hz for analyses (Ema et al., 2018a). The twitch peak torque was normalized to the body mass, and $\text{RTD}_{\text{twitch}}$ was normalized to two-thirds power (i.e., $0.67$) of body mass (Jaric et al., 2005). The torque onset was manually identified as the last peak or trough within the baseline noise envelope, in accordance with previously described procedures (Ema et al., 2018a; Tillin et al., 2010). To obtain $H_{\text{max}}$, the stimulation intensity was increased in 1-mA increments until the maximal amplitude for the SOL H-reflex was identified. Stimulation was applied twice at each intensity, with 10-s intervals between stimulations, and the mean H-reflex amplitude was recorded. The $H_{\text{max}}$ of LG was not included in further analyses because of the difficulty in detecting a clear wave from a number of participants. The $H_{\text{max}}$ was normalized to the $M_{\text{max}}$.

2.5. MVC and VA%

The participants completed a warm-up procedure involving sub-maximal contractions followed by two planter flexor MVCs in K0 and K90. The participants exerted plantar flexor force as strongly as possible for 3 s with verbal encouragement, with 1-min rest between contractions. If the difference in peak torque between the two contractions was above 10%, additional contractions were performed with sufficient rest between the contractions. Two dorsiflexor MVCs in K0 were conducted to obtain the maximal activity of the TA as the agonist. The peak torque of each contraction was defined as the MVC torque, and normalized to the body mass (Jaric et al., 2005). The root mean square values for the EMG signals (RMS-EMGs) from MG, LG and SOL during MVC were determined over a 0.5-s period around the maximal torque, and were normalized to $M_{\text{max}}$. The RMS-EMG of TA during MVC was normalized to that during the dorsiflexor MVC. The mean values of the two contractions were used for later analyses.

Two additional plantar flexor MVCs were performed to assess VA% using the twitch interpolation technique, with the same rest to MVC between contractions. Supramaximal twitch stimulation was delivered during and 2 s after plantar flexor MVC. The VA% was determined using the following formula: 

$\text{VA}% = \left(1 - \frac{\text{superimposed twitch torque/\text{potentiated resting twitch torque}}}{}\right) \times 100$.

The mean of the two contractions was used for later analyses.

2.6. Explosive strength

Participants conducted 10 explosive voluntary plantar flexions. The participants were encouraged to exert plantar flexion force as fast and forcefully as possible every 20 s for ~1 s, with an emphasis on fast. Contractions with an unstable baseline (countermovement or pre-tension) of $>0.5$ Nm in the 200 ms prior to contraction onset were excluded from the analyses. The three contractions with the largest peak slopes and peak torque above 70% of the MVC torque were used for later analyses. The RTD was defined (Fig. 2) as the slope of the time-torque curve at time points between the onset of plantar flexion and 50 ms ($\text{RTD}_{50}$) and between 100 and 200 ms ($\text{RTD}_{100-200}$) (Gersten et al., 2017; Thompson et al., 2014), and normalized to the power of 0.67 of body mass (Jaric et al., 2005). The RMS-EMGs of the triceps surae were calculated over the same time periods as the RTD from the onset of the EMG amplitude and normalized to $M_{\text{max}}$ for each muscle. We did not obtain the RMS-EMG of TA during explosive contractions due to the low repeatability of measurements for antagonist EMG (Ema et al., 2018a). The force and EMG onsets were manually determined as in previous studies (Ema et al., 2018a; Tillin et al., 2010). In addition, the electro-mechanical delay (EMD) of MG was determined as the time difference between the onsets of plantar flexion and the MG EMG amplitude. In the fully knee extended with the ankle joint in the anatomical position, MG EMD was less affected by slack in the Achilles tendon (Muraoaka et al., 2004). In the position, a negative correlation between MG EMD and Achilles tendon stiffness and a positive correlation between Achilles tendon stiffness and explosive plantar flexion strength have been observed (Waugh et al. 2013). Changing the knee joint angle did not affect the length of the external tendon of MG (Wakahara et al. 2005), suggesting that EMD of MG in K90 would be also less affected by the slack. Based on these findings, we determined MG EMD as an indirect indicator of the tendon mechanical properties in K0 and K90.

2.7. Muscle architecture

Using B-mode ultrasonography, the muscle thickness was determined during quiet standing at 30% of the lower leg length from the popliteal crease to the lateral malleolus for LG and SOL with a linear array probe (9L4 Transducer, Siemens Medical Solutions, USA) (Fig. 3). MG thickness in K0 and penman angle in K0 and K90 were obtained by another linear array probe (18 L6 Transducer, Siemens Medical Solutions, USA) at 40% of the lower leg length (Ema et al. 2017) on the bench of the dynamometer. The muscle thickness was defined as the mean of the distances between superficial and deep aponeuroses measured at both ends of each image with a width of 45 mm (LG and SOL) or 60 mm (MG), and normalized to one-third power of the body mass. Penman angle was determined as the angle between the fascicle and deep aponeurosis (Narici et al. 1996). Previously, penman angles of MG, LG, and SOL were found to be smaller in YM than in OM with the similar magnitude of age-related differences among the muscles (Morse et al., 2005). This suggests that the value of one of the three muscles seem to
represent the corresponding age-related difference in the whole triceps surae. Kawakami et al. (1998) demonstrated that knee flexion increased MG pennation angle but LG and SOL pennation angles were less or no changed. Thus, the present study focused on MG pennation angle. The measurement was performed three times. The analyses were conducted with Image J (National Institute of Health, USA) and the mean value was used for later analyses. The means of coefficient of variation (CV) in the analyses of the three images were 4.0–6.3% for muscle thickness and 3.2–3.4% for pennation angle, respectively.

### 2.8. Statistical analyses

Statistical analyses were performed using SPSS version 25 (IBM, USA). The normality of data distribution was examined with the
Shapiro–Wilk test. When the normality was violated, the data were log-transformed. All data are shown as means ± SD of raw data to facilitate the interpretation. A three-way analysis of variance (ANOVA) with two between-group factors (age [older and young] and sex [males and females]) and one within-group factor (angle [K0 and K90] or muscle [MG, LG, SOL]) was conducted on the dependent variables. When a significant interaction was detected, follow-up ANOVAs with Bonferroni multiple-comparisons were used. According to a previous study (Andersen and Aagaard 2006), the relationship between RTD\textsubscript{twitch} and RTD\textsubscript{0–50} in each sex was tested using Pearson product moment correlation coefficient (r). Statistical significance was set at $P < 0.05$. For variables that showed a significant difference between ages or between knee positions, Cohen’s d in between-subject designs (Lakens 2013) was calculated as an index of effect size (ES), and 90% confidence intervals (90%CI) were obtained (Hopkins 2007). We interpreted whether the effect of age in K0 was substantial (ES for age) and whether the effect of the knee joint angle substantially differed between older and young adults (ES for age × angle) in each sex. The thresholds were 0.20, 0.60, and 1.20 for small, moderate, and large ES, respectively (Hopkins et al. 2009). When the ES was $\geq 0.20$ and the lower limit of the 90%CI for ES was $\geq -0.20$ with $P < 0.05$, we considered that the age effect was substantial or the knee joint angle effect substantially differed between ages.

**Fig. 4.** Evoked peak twitch torque of plantar flexion (A), time to the peak twitch torque (B), rate of torque development of the twitch (RTD\textsubscript{twitch}, C), and peak-to-peak amplitude of H-reflex ($H_{\text{max}}$) for the medial gastrocnemius (MG, D) and soleus (SOL, E) in fully extended (K0) and 90° flexed (K90) knee positions. Data are shown as mean ± standard deviation. $H_{\text{max}}$ was normalized to the peak-to-peak compound muscle action potential amplitude ($M_{\text{max}}$). Scatterplots show individual data. *Indicates a significant difference between K0 and K90. †Denotes a significant difference between older and young adults. OF, older females; OM, older males; YF, young females; YM, young males.
3. Results

F values and partial eta squared for ANVOAs were reported in a Supplementary file (Appendix A).

3.1. Evoked variables

No age-related difference was found for the twitch peak torque. A significant main effect of angle (P < 0.001) demonstrated a significantly greater peak twitch torque in K0 than in K90 (Fig. 4). There were a main effect of age and a sex × angle interaction (P ≤ 0.007) for TPT. The TPT was significantly longer in older than young adults, and in K90 than in K0 for males. The interaction of age × angle for RTD\textsubscript{twitch} was significant (P < 0.001), and post-hoc tests indicated that the values were significantly greater in young than in older adults in K0, and in K0 than in K90 in both ages. For H\textsubscript{max}, because we did not obtain a clear wave for some participants, the number of participants was reduced (OM = 10; OF = 11; YM = 18; YF = 16). The main effects of age and angle for MG, and age × sex × angle interaction for SOL were significant (P ≤ 0.012). The H\textsubscript{max} of MG was significantly higher in younger adults and in K90. The SOL H\textsubscript{max} was higher in younger individuals regardless of the sex or knee joint angle, and higher in K0 for OW, YM, and YW.

Fig. 5. Peak torque during maximal voluntary contraction (MVC) of plantar flexion (A), voluntary activation (VA%) during MVC (B), root mean square of the electromyogram (RMS-EMG) of the medial gastrocnemius (MG, C), lateral gastrocnemius (LG, D), soleus (SOL, E), and tibialis anterior (TA, F) in fully extended (K0) and 90° flexed (K90) knee positions. Data are shown as mean ± standard deviation. RMS-EMGs of the triceps surae were normalized to the peak-to-peak compound muscle action potential amplitude (M\textsubscript{max}), and RMS-EMG of TA was normalized to that during dorsiflexor MVC. Scatter plots show individual data. * Indicates a significant difference between K0 and K90. † Denotes a significant difference between older and young adults. ‡ Shows a significant difference between males and females at each age. § Demonstrates a significant difference between males and females irrespective of age. || Displays a significantly higher value in young adults than in older adults in K0. OF, older females; OM, older males; YF, young females; YM, young males.
3.6. Interpretations of the magnitude of effects

There were significant interactions of age × angle and age × sex (P = 0.001–0.028) for MVC torque. The MVC torque was 25–44% greater in young than in older adults, and 20–23% greater in YM than in YW (Fig. 5), and 11–21% greater in K0 than in K90. There were main effects of age and sex (P = 0.024–0.031) for VA%. The VA% was significantly higher in younger adults and in men. Regarding RMS-EMGs, a significant age × angle interaction effect and main effect of sex for RMS-EMG of MG and LG and main effect of sex for SOL were found (P ≤ 0.048). In K0, the MG RMS-EMGs of young adults were significantly higher than those of older adults. The RMS-EMGs of MG and LG were significantly higher in K90 than in K0 in older adults, and vice versa for that of MG in young adults. No main effect or interaction was found for TA.

3.3. Variables during explosive contractions

The RTDs and RMS-EMGs are demonstrated in Fig. 6. A significant interaction of age × angle (P = 0.001) for RTD<sub>T0.50</sub> and interactions of age × angle and age × sex (P = 0.001–0.043) for RTD<sub>T0.200.200</sub> were found. The RTD<sub>T0.50</sub> and RTD<sub>T0.200.200</sub> were 20–48% greater in young than in older adults. Sex difference was found for RTD<sub>T0.200.200</sub> in young adults, with greater in YM than in YF. Between knee positions, RTDs in K0 were 14–22% greater than those in K90 for young adults only. As for RMS-EMGs, there were a significant age × angle interaction and a main effect of sex for MG and LG at both 0–50 ms and 100–200 ms, and main effect of sex for SOL (P = 0.009). In K0, young adults showed higher MG RMS-EMGs than older adults whereas the opposite results were obtained in K90 for MG (both time intervals) and LG (0–50 ms). For comparisons of knee positions, MG RMS-EMGs were significantly higher in K90 for older adults and vice versa for young adults. Older adults had higher LG RMS-EMG values in K90 than in K0 at 100–200 ms, whereas young adults had lower values in K90 than in K0 at 0–50 ms. The significant main effect of sex (P = 0.004) demonstrated that the MG EMDs of females (YF: K0, 37 ± 13 ms, K90, 42 ± 17 ms; OF: K0, 44 ± 22 ms, K90, 43 ± 20 ms) were significantly longer than those of males (YM: K0, 31 ± 12 ms, K90, 30 ± 10 ms; OM: K0, 33 ± 12 ms, K90, 35 ± 14 ms).

3.4. Muscle architecture

Because of mechanical accident, ultrasound images of one OM could not be obtained. A significant interaction of age × sex × muscle for muscle thickness and age × sex interaction and main effect of angle for pennation angle of MG were found (P ≤ 0.042). The MG (both sexes) and LG (men) thickness was 10.0–31.5% greater in young adults than in older adults, and OF had greater MG thickness compared with OM (Table 1). In contrast, no significant age- or sex-related difference was found for SOL thickness. The MG pennation angle was greater in YM than OM and YF, and K0 than in K90.

3.5. Relationship between RTD<sub>twitch</sub> and RTD<sub>T0.50</sub>

In males (n = 35), RTD<sub>twitch</sub> was positively correlated with RTD<sub>T0.50</sub> in K0 (r = 0.596, P < 0.001) and K90 (r = 0.412, P = 0.014). Similarly, positive correlations were shown for females (n = 34; K0, r = 0.513, P = 0.002; K90, r = 0.563, P = 0.001).

3.6. Interpretations of the magnitude of effects

Regarding the variables that showed significant differences between ages (Table 2) or knee positions (Table 3), ES and its 90%CI are shown. It should be noted that the ESs for age on the variables of evoked and early RTDs were higher in females (ES = 0.63–1.90) than in males (ES = 0.46–1.21), and vice versa for later RTDs and MVC (ES = 0.32–1.06 for females and 0.79–2.35 for males). Similarly, the ES for the age × angle on RTD<sub>T0.50</sub> was higher in females (ES = 0.75, moderate) than males (ES = 0.59, small) and vice versa for RTD<sub>T0.200.200</sub> and MVC torque (males, ES = 0.98–1.14, moderate; females, ES = 0.43–0.55, small).

4. Discussion

Older adults displayed smaller MVC torque and RTDs at early and later phases than young adults. The MVC torque and RTD<sub>T0.200.200</sub> were smaller in YF than in YM, but the corresponding sex difference was not significant in older adults. The age effect on the two variables was large for males (ES = 2.14–2.35) and moderate for females (ES = 0.76–1.06), whereas that on RTD<sub>T0.50</sub> was higher for females (ES = 1.36, large) than for males (ES = 1.03, moderate). These results suggest that females showed greater age-related reductions of RTD at the early phase while males did so at the later phase of RTD and MVC torque. For older individuals, voluntary RTDs were not significantly different between K0 and K90, and the knee joint angle provided opposite influence on neuromuscular activations of the gastrocnemius between ages. The ES for age × angle of RTD<sub>T0.50</sub> was higher for females (ES = 0.75, moderate) than males (ES = 0.59, small), whereas those of the MVC torque and RTD<sub>T0.200.200</sub> were higher for males (ES = 0.98–1.14, moderate) than females (ES = 0.43–0.55, small). These results show that the effect of knee joint angle on maximal and explosive strength was substantially different between older and young adults, and the difference in the early phase of force production was more apparent in females, and in the later phase of force production and maximal force were more evident in males. Thus, our hypothesis was supported.

4.2. Effect of age

A relatively large effect of age on RTD<sub>T0.50</sub> was observed for females. TPT was longer and RTD<sub>twitch</sub> was smaller in older adults, with large ESs for females and moderate ESs for males. The results suggest that the speed of the muscle twitch decreases with age, particularly in females. A previous study (Andersen and Aagaard 2006) demonstrated that RTD<sub>twitch</sub> was positively correlated with the early but not the later phases of RFD. Consistent with the previous study, the current study confirmed the positive correlations between RTD<sub>twitch</sub> and RTD<sub>T0.50</sub> in both sexes. In addition, the effect of age on MG RMS-EMG<sub>T0.50</sub> was greater for females (ES = 0.63, moderate) than males (ES = 0.46, small). Accordingly, age- and sex-related differences in RTD at the early phase can be explained by the concomitant differences in the intrinsic muscle contractile properties and neuromuscular activation of MG.

Males showed greater age-related differences in MVC torque and RTD<sub>T0.200.200</sub>. The sizes of MG (both males and females) and LG (only men) were substantially smaller in older adults, and OM had smaller MG thickness than OF without the corresponding difference in young adults. In contrast, SOL thickness was not different between the ages. These results suggest that greater age-related atrophy of the gastrocnemius occurred in males than in females, corroborating previous studies (Fujiwara et al., 2015; Morse et al., 2005). The inferior muscularity of the gastrocnemius, especially in OM, seems attributable to the age-related atrophy of fast twitch fibers (Lexell et al. 1988) and the fact that males have more fast twitch fibers than females (Hunter 2014). Although twitch peak torque was not significantly different between older and young adults (thus no data of ES in Table 2), this may be related to low sensitivity of twitch torque to detect differences compared with doublet torque (Maffioletti and Lepers 2003). Additional calculated age effect of the twitch peak torque in K0 was higher in males (ES = 0.70 [moderate], 90% CI 0.13 to 1.28) than in females (ES = 0.48 [small], 90% CI −0.11 to 1.06). The effect of knee position on the twitch torque was also substantially different between ages, with a moderate effect for males and a small effect for females, respectively (Table 3). These twitch results were probably associated with age-related impairment of the maximal force-generating potential of the biarticular gastrocnemius,
Fig. 6. Rate of torque development (RTD, A and E) of plantar flexion and root mean square of the electromyogram (RMS-EMG) during explosive contraction of the medial gastrocnemius (MG, B, and F), lateral gastrocnemius (LG, C, and G), and soleus (SOL, D and H) in fully extended (K0) and 90° flexed (K90) knee positions. Data are shown as mean ± standard deviation. RTD was defined as the slope of the time-torque curve during time intervals of 0–50 ms and 100–200 ms from the onset of plantar flexion. RMS-EMGs of the triceps surae were normalized to the peak-to-peak compound muscle action potential amplitude (M\text{max}). Scatterplots show individual data. *Indicates a significant difference between K0 and K90. †Denotes a significant difference between older and young adults. ‡Shows a significant difference between males and females at each age. §Demonstrates a significant difference between males and females irrespective of age. ||Displays a significantly higher value in young than in older adults in K0. ¶Describes a significantly higher value in older than in young adults in K90. OF, older females; OM, older males; YF, young females; YM, young males.
especially for males, resulting in the current results for MVC torque and RTD\textsubscript{100-200}.

With respect to the neural factors associated with the greater age-related differences in the strength for males, VA% can be considered. VA% was higher in young than older adults, which is not consistent with previous studies that observed similar VA% between older and young adults (Hunter et al. 2008; Jakobi and Rice 2002). Both older and younger participants performed the same familiarization, and the means of the CV of VA% in the two MVC were similar between the age groups (3.0–5.9% for older adults and 2.7–4.3% for young adults). Thus, it seems difficult to consider that the age-related difference in the VA% was owing to limited familiarization or not enough practice for the older adults. The most likely explanation for the discrepancy between studies is that the number of participants (37 young and 32 older adults) in the current study was larger than that in the previous studies (Hunter et al. 2008 [17 young and 7 older adults]; Jakobi and Rice 2002 [6 young and 6 older adults]), and the present study involved a within-group factor (i.e., measurements in K\textsubscript{0} and K\textsubscript{90}). Thus, the main effect of age was likely to be obtained even though the effect size was not large. The novel finding in the present study was that the ESs were moderate for males (Figs. 5C, and 6F) may imply the age-related attenuated ability to recruit MG during contractions.

Fascicle arrangement and tendon mechanical properties can also

Table 2

| Variables                        | Males        | Cohen’s d | 90%CI       | Females       | Cohen’s d | 90%CI       |
|----------------------------------|--------------|-----------|-------------|--------------|-----------|-------------|
| Evoked strength variables        |              |           |             |              |           |             |
| Twitch peak torque               | 1.08         | *         | 0.51 to 1.65| 0.49         | *         | −0.09 to 1.08|
| TPT                              | 0.04         |           | −0.54 to 0.61| 1.05         | *         | 0.46 to 1.63 |
| RTD\textsubscript{twitch}        | 1.03         | *         | 0.46 to 1.61| 0.29         |           | −0.29 to 0.88|
| H\textsubscript{max} of MG       | 0.05         |           | −0.52 to 0.63| 1.11         |           | −0.48 to 0.69|
| H\textsubscript{max} of SOL      | 0.78         | *         | 0.21 to 1.35| 0.55         | *         | −0.03 to 1.14|
| MVC variables                    |              |           |             |              |           |             |
| MVC torque                       | 1.14         | *         | 0.56 to 1.71| 1.19         | *         | 0.60 to 1.77 |
| RMS-EMG of MG                    | 0.80         | *         | 0.23 to 1.37| 0.96         | *         | 0.36 to 1.55 |
| RMS-EMG of LG                    | 0.95         | *         | 0.38 to 1.53| 0.75         | *         | 0.16 to 1.33 |
| Explosive strength variables     |              |           |             |              |           |             |
| RTD\textsubscript{p-50} of MG    | 0.94         | *         | 0.37 to 1.51| 1.40         | *         | 0.82 to 1.99 |
| RMS-EMG\textsubscript{p-50} of MG| 1.17         | *         | 0.60 to 1.75| 0.62         | *         | 0.02 to 1.21 |
| RTD\textsubscript{100-200}       | 0.99         |           | 0.41 to 1.56| 0.43         | *         | −0.15 to 1.02|
| RMS-EMG\textsubscript{100-200} of MG| 0.79   | *         | 0.22 to 1.36| 0.98         | *         | 0.40 to 1.57 |
| Muscle architecture              |              |           |             |              |           |             |
| MG pennation angle               | 0.37         | *         | −0.20 to 0.94| 0.14         |           | −0.44 to 0.73|

Cohen’s d was calculated for the variables in the extended knee position that showed significant differences between ages. Therefore, the blank shows that the variable was not significantly different between knee positions. *Indicates that the effect of knee joint angle was substantial in each sex. CI, confidence interval; H\textsubscript{max}, peak-to-peak amplitude of H-reflex; LG, lateral gastrocnemius; MG, medial gastrocnemius; MVC, maximal voluntary contraction; RMS-EMG, root mean square of the electromyogram; RTD, rate of torque development; SOL, soleus; TPT, time to peak twitch torque; VA%, voluntary activation.

Table 3

Age-related difference in the effect of knee joint angle in each sex.

| Variables                        | Males        | Cohen’s d | 90%CI       | Females       | Cohen’s d | 90%CI       |
|----------------------------------|--------------|-----------|-------------|--------------|-----------|-------------|
| Evoked strength variables        |              |           |             |              |           |             |
| Twitch peak torque               | 1.08         | *         | 0.51 to 1.65| 0.49         | *         | −0.09 to 1.08|
| TPT                              | 0.04         |           | −0.54 to 0.61| 1.05         | *         | 0.46 to 1.63 |
| RTD\textsubscript{twitch}        | 1.03         | *         | 0.46 to 1.61| 0.29         |           | −0.29 to 0.88|
| H\textsubscript{max} of MG       | 0.05         |           | −0.52 to 0.63| 1.11         |           | −0.48 to 0.69|
| H\textsubscript{max} of SOL      | 0.78         | *         | 0.21 to 1.35| 0.55         | *         | −0.03 to 1.14|
| MVC variables                    |              |           |             |              |           |             |
| MVC torque                       | 1.14         | *         | 0.56 to 1.71| 1.19         | *         | 0.60 to 1.77 |
| RMS-EMG of MG                    | 0.80         | *         | 0.23 to 1.37| 0.96         | *         | 0.36 to 1.55 |
| RMS-EMG of LG                    | 0.95         | *         | 0.38 to 1.53| 0.75         | *         | 0.16 to 1.33 |
| Explosive strength variables     |              |           |             |              |           |             |
| RTD\textsubscript{p-50} of MG    | 0.94         | *         | 0.37 to 1.51| 1.40         | *         | 0.82 to 1.99 |
| RMS-EMG\textsubscript{p-50} of MG| 1.17         | *         | 0.60 to 1.75| 0.62         | *         | 0.02 to 1.21 |
| RTD\textsubscript{100-200}       | 0.99         |           | 0.41 to 1.56| 0.43         | *         | −0.15 to 1.02|
| RMS-EMG\textsubscript{100-200} of MG| 0.79   | *         | 0.22 to 1.36| 0.98         | *         | 0.40 to 1.57 |
| Muscle architecture              |              |           |             |              |           |             |
| MG pennation angle               | 0.37         | *         | −0.20 to 0.94| 0.14         |           | −0.44 to 0.73|

Cohen’s d was calculated for the variables that showed significant differences between knee positions. Therefore, the blank shows that the variable was not significantly different between knee positions. *Indicates that the effect of knee joint angle was substantially different between older and young adults in each sex. CI, confidence interval; H\textsubscript{max}, peak-to-peak amplitude of H-reflex; LG, lateral gastrocnemius; MG, medial gastrocnemius; MVC, maximal voluntary contraction; RMS-EMG, root mean square of the electromyogram; RTD, rate of torque development; SOL, soleus; TPT, time to peak twitch torque; VA%, voluntary activation.

- “RTD” means the rate of torque development.
- “SOL” stands for the soleus muscle.
- “TPT” refers to the time to peak twitch torque.
- “VA%” denotes the voluntary activation.
- “Cohen’s d” represents the effect size.
- “90%CI” indicates the 90% confidence interval.
- “PNN” stands for peroneus longus, tibialis anterior, and extensor hallucis longus.
- “H-reflex” signifies the H-reflex amplitude.
- “MG” stands for the medial gastrocnemius muscle. Additionally, “LG” stands for the lateral gastrocnemius muscle.

Specifically, for older adults, the number of participants (37 young and 32 older adults) in the current study was larger than that in the previous studies (Hunter et al. 2008 [17 young and 7 older adults]; Jakobi and Rice 2002 [6 young and 6 older adults]), and the present study involved a within-group factor (i.e., measurements in K\textsubscript{0} and K\textsubscript{90}). Thus, the main effect of age was likely to be obtained even though the effect size was not large. The novel finding in the present study was that the ESs were moderate for males. The novel finding in the present study was that the ESs were moderate for males (Figs. 5C, and 6F) may imply the age-related attenuated ability to recruit MG during contractions.
affect the age-related differences in explosive strength. OM had smaller MG pennation angle than YM (Table 1). This is consistent with a previous study that observed smaller pennation angles of MG, LG and SOL in OM than in YM (Morse et al., 2005). The present study added the evidence that the mean value was smallest in OM among the participants (Table 1). A negative impact of the pennation angle on RTD at a later phase has been reported (Erskine et al. 2014). Therefore, the greater age-related differences in RTD_{100–200} for males than females may not be explained by the pennation angle. Because we did not assess LG and SOL pennation angles, future study is required to clarify the whole picture of the effect of fascicle arrangement on age-related differences in RTD. Additionally, no age effect was indicated for MG EMD. As MG EMD was negatively correlated with Achilles tendon stiffness (Waugh et al., 2013), a substantial effect of the tendon mechanical properties on the present findings seems unlikely.

4.3. Effect of knee joint angle

Previous studies reported a greater MVC torque in an extended knee position than in a flexed knee position for YM (Cresswell et al., 1995; Dalton et al., 2013; Hall et al., 2019; Kennedy and Cresswell, 2001; Wakahara et al., 2007) and OM (Dalton et al., 2014). The current study added evidence that such findings can be expanded to females and early and later phases of RTDs for young adults. The results of the MVC torque and RTDs in older adults support those of a previous study in which higher MVC torque but not plantar flexor power was observed in an extended knee position compared to a flexed knee position for OM (Dalton et al., 2014). The present study is the first to show that the effect of the knee joint angle was substantially different between older and young adults for the MVC torque as well as for the RTDs (Table 3), especially in females for the early phase of force production and in males for the later phase and MVC. Among the constituents of the triceps surae, only SOL activation during voluntary contraction was not different between K0 and K90, which supports a previous finding (Cresswell et al., 1995). Also, antagonist TA activation was not affected by knee joint angle. Thus, the neuromuscular factors affecting the contribution of the gastrocnemius to the plantar flexion torque can be explored.

The results of twitch torque (Fig. 4) indicated that the length-dependent force-generating capabilities of the gastrocnemius were higher in K0 than in K90 irrespective of age and sex. The decrease in the capacity by knee flexion would have been greater for young than older adults, particularly in males (ES = 1.08 for males and 0.49 for females, Table 3). This was attributed to the reduced contribution of the gastrocnemius force to plantar flexion torque owing to selective atrophy of the gastrocnemius in OM than OF (Table 1). Such muscularity would have reduced the differences in the plantar flexion torque between the knee positions for older adults compared with young adults, especially for men.

Regarding neuromuscular activations, a previous study (Hall et al., 2019) demonstrated that the recruitment thresholds of MG and LG motor units during contractions were higher and the firing rate of MG motor units was lower in a flexed knee position compared to an extended knee joint position for YM. Such inhibitions would be associated with lower MG and LG RMS-EMGs in K90 than in K0 for young adults (Figs. 5 and 6). In contrast, MG and LG activations were higher in K90 than in K0 for older adults in the present study, diminishing the strength differences between the knee positions. In particular, age-related difference in the effect of knee joint angle on RMS-EMG_{RMS} of MG was greater for females than males, being likely to be related to the corresponding difference in RTD_{100–200}. Kirk et al. (2016) reported no age-related differences in MG and LG motor unit firing rates during maximal and submaximal plantar flexion in a flexed knee position. In their study (Kirk et al., 2016), the EMG amplitudes of the muscles at submaximal contraction levels were higher in OM than in YM, owing to increased recruitment of motor units. Unfortunately, they did not report the data for an extended knee position, but considering the current results, older adults may show different motor unit control strategies associated with the knee position compared to young adults.

As mentioned above, the increase in pennation angle may affect RTD at later phase negatively (Erskine et al. 2014). Previously, the effect of knee joint angle on pennation angle was greater for MG than LG or SOL (Kawakami et al., 1998), although older adults were not involved as the participants in their study. Thus, the effect of possible changes in the LG and SOL pennation angles by knee flexion on RTD would be smaller than that of MG. The greater MG pennation angle in K90 than in K0 for young adults (Table 1) may be partly related to the lower RTD_{100–200} in K90 than in K0. Moreover, age-related difference in the effect of knee joint angle on pennation angle was substantial for males (Table 3), being likely to be related to moderate ES for age \(\times\) angle for RTD_{100–200}. Older adults also displayed an increase in pennation angle with knee flexion, but the significant difference in RTD_{100–200} was not observed between K0 and K90. It is possible, therefore, that the effect of changes in pennation angle with changes in knee joint angle on explosive strength may be different between young and older adults.

4.4. Limitation

There are some limitations that should be considered in future studies. First, it is unclear whether the findings obtained from the current participants are applicable to general population. The magnitude of physical activity in older adults aged 65 to 74 yr who had no cognitive problems (Tomioka et al., 2011) was lower than that of the current study. Thus, the present findings may be limited to relatively active older adults. Second, this study did not obtain any data that clearly detected motor unit behavior. A previous study (Klass et al. 2008) demonstrated that the age-related decreases in the dorsiflexor RTD was due to both a slowing of the contractile properties of TA muscle and a decrease in the maximal discharge frequency of motor units. We discussed the effect of former point in the previous paragraph, but clarification of the effects of age, sex, and knee position on motor unit behavior during plantar flexion is the next step. Third, some participants showed relatively low VA%. Thus, greater familiarization may have been required for both age groups to ensure that participants could achieve high VA%. Finally, which level the neural drive is controlled is difficult to describe from the present results. Del Vecchio et al. (2019) suggested that neural drive during explosive contraction was originated from cortical level for the TA. In the current study, H_{max} which reflects the spinal excitability was smaller in older adults than in young adults (Fig. 4), and the effect of age was greater for females than for males (Table 2). Previously, acute decrease in H-reflex amplitude was not accompanied by changes in the EMG (Ushiyama et al., 2005) or maximal and explosive strengths (Fry and Folland, 2014). Moreover, the compensatory mechanisms at the supra-spiral level for reduced spinal excitability in older adults were reported (Baudry et al. 2014). Therefore, age-related decreases in H_{max} may have not substantially affected the neuromuscular performance of the triceps surae.

4.5. Practical implication

The current findings have some practical implications for plantar flexor exercises. First, females should perform exercise with the intent to move rapidly, because such exercise improved RTD and MG activations, especially in the early phase of explosive contractions (Ema et al. 2017). Second, MVC exercises may be useful for males considering that MVC training was better to improve MVC strength as compared with explosive type of training (Balshaw et al., 2016). Finally, reconsideration of exercise regimen in relation to knee joint angle during the exercise may be needed. For example, it was proposed that heel-raise exercise should be performed in the fully extended knee position to improve neuromuscular performance of the gastrocnemius (Signorile et al., 2002). This proposal was based on results obtained from participants aged 19–51 yr. However, the present study showed that RMS-EMGs of the MG and LG...
during MVC and explosive contractions were higher in K90 than in K0 for older adults. Thus, plantar flexor exercises at flexed knee position may be a better choice for older adults to improve neuromuscular performance of the triceps surae rather than at extended knee position, although the training specificity of joint angle (Kitai and Sale 1989) may be taken into account.

4.6. Conclusion

The present study revealed the existence of age-related differences in plantar flexor MVC torque and RTDs at early and later phases in both sexes. The findings suggested that age-related attenuation of the early phase RTD is greater in females whereas attenuation of the later phase RTD and MVC torque is greater in males. The knee joint angle had different effects on the maximal and explosive plantar flexion strengths between older and young adults. The age-related difference in the effect of the knee position on RTD at an early phase was greater for females than for males, and vice versa at a later phase and MVC torque.

CRediT authorship contribution statement

Ryoichi Ema: Conceptualization; Methodology; Formal analysis; Investigation; Writing - Original Draft; Visualization; Project administration; Funding acquisition
Emi Kawaguchi: Formal analysis; Investigation; Writing - Review & Editing
Momoka Suzuki: Formal analysis; Investigation; Writing - Review & Editing
Ryota Akagi: Conceptualization; Methodology; Writing - Review & Editing; Supervision; Project administration

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Declaration of competing interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejger.2020.111148.

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