

Muscle mechanical and architectural adaptations in response to different endurance training modalities in older adults[☆]

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ABSTRACT

Introduction: This study examined the effects of various cycling endurance training modalities, matched for total workload, on muscle mechanical and architectural characteristics in older adults.

Methods: Fifty healthy participants (25 females, 59–79 yrs) were randomly assigned to five age and sex matched groups: one control and four workload-matched training groups (moderate-intensity continuous, heavy-intensity continuous, high-intensity interval, and heavy-intensity continuous in eccentric cycling). Training consisted of three weekly sessions over 8 weeks, with evaluations conducted at the beginning and end of the intervention with maximal voluntary isometric contractions at five different knee angles (90, 75, 60, 45, 30°) and maximal concentric and eccentric isokinetic contractions at five different knee angular velocities (45, 90, 150, 210, 250°/s). Maximum voluntary isometric torque (T_{max}) and optimal knee angle (KA_{opt}) were obtained from the isometric contractions; eccentric torque (T_{ecc}) and maximum concentric knee angular velocity (V_{max}) were obtained from the isokinetic contractions. The muscle architecture of vastus lateralis (VL) at rest (muscle thickness, pennation angle, and fascicle length) was investigated as well.

Results: No statistical differences were detected between groups or time points in VL architecture, in KA_{opt} and in V_{max} . A main effect of time was observed for T_{max} ($p < 0.001$, $\eta_p^2 = 0.458$) and T_{ecc} ($p = 0.002$, $\eta_p^2 = 0.191$) in all the investigated training groups. The within-group comparisons indicate significant increases in T_{max} in the training groups, but not in the control group.

Conclusions: Commonly applied endurance exercises improve muscle mechanical capacity (T_{max} and T_{ecc}) in older adults, with no structural (architectural) muscle remodelling, when matched for workload.

1. Introduction

With ageing, skeletal muscles undergo a progressive loss of volume (Horwath et al., 2025) and function (Kent-Braun and Ng, 1999), with changes in muscle architecture (Lexell et al., 1988; Narici et al., 2003). These changes significantly affect the force-velocity and the force-length relationships (Lanza et al., 2003; Morse et al., 2005; Ochala et al., 2004; Thom et al., 2007) and the torque-angle (T-A) and torque-velocity (T-V) relationships. On one hand, a shift in the T-A relationship, often alters the range of motion where peak torque occurs (Simoneau et al., 2007). On the other hand, a downward shift of the T-V relationship has been typically observed with older adults, producing less torque at all contraction velocities; this decrease is more pronounced at higher velocities (Lanza et al., 2003), leading to reduced muscle power and

reduced function in rapid movements (Callahan and Kent-Braun, 2011).

While, in older adults, the T-A relationship is traditionally more studied than the T-V relationship due to the technical challenges of dynamic testing (Callahan and Kent-Braun, 2011; Lanza et al., 2003), recent evidence highlights that investigating the T-V relationship under both concentric and eccentric conditions provides crucial insights. Notably, eccentric strength appears to be relatively preserved with ageing (Alcazar et al., 2023; Reid and Fielding, 2012; Roig et al., 2010), suggesting that different contraction modes are selectively affected over the lifespan (Douglas et al., 2017; Roig et al., 2010).

The decline in muscular strength and power (Lieber and Fridén, 2000), along with other factors such as the ageing of the somatosensory and motor nervous systems (Edström et al., 2007; Shaffer and Harrison, 2007), lead to a reduced capacity to undertake activities of

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daily living (Cameron et al., 2023; Bottaro et al., 2007; Doherty, 2003), increased risk of falling (Orr et al., 2006; Skelton, 2002), loss of independence and reduction in the quality of life (Doherty, 2003). To mitigate these functional declines and preserve independence, endurance exercise in its different forms (e.g., walking, running, and cycling) is widely recommended as a primary strategy to optimize health trajectories in older adults (Carapeto and Aguayo-Mazzucato, 2021).

However, while the cardiovascular and metabolic benefits of endurance training are extensive and well documented (Cadore, 2014; Carrick-Ranson et al., 2023; Sillanpää et al., 2009) its potential to induce muscle mechanical and structural adaptations has received much less attention, and the few available studies have yielded inconsistent results. Specifically, the effects of endurance training on structural properties in older adults remain controversial. Cross-sectional evidence suggests that long-term endurance exercise may be insufficient to fully preserve age-related alterations in muscle geometry. For example, McKendry et al. (2020) reported that master endurance athletes with approximately 37 years of training experience did not exhibit greater muscle thickness, pennation angle, or fascicle length than age-matched sedentary older adults. Conversely, Stenroth et al. (2017) suggested that endurance training may induce architectural adaptations that are beneficial for movement economy in older adults. Furthermore, Bruseghini et al. (2019) demonstrated that eight weeks of high-intensity aerobic training increased muscle cross-sectional area and pennation angle in older adults, suggesting that exercise intensity may play a key role in driving architectural remodelling.

These findings indicate that while endurance training can influence skeletal muscle structure, the extent and nature of these adaptations may depend on the specific characteristics of the training stimulus. In particular, the role of exercise intensity in promoting muscle architectural adaptations in older adults remains poorly understood. A major confounding factor in interpreting the existing literature is the variation in training dose. Differences in frequency, volume, and intensity across studies make it challenging to isolate which specific “ingredient” of the exercise prescription drives muscle remodelling. Investigating these adaptations at an invariant total workload is therefore essential to clarify the independent effects of exercise intensity and contraction type.

In this context, another form of endurance training, called eccentric cycling, has emerged as a promising training modality for older and fragile populations. By resisting motorized pedals, individuals perform eccentric contractions that entail a significantly lower metabolic and cardiopulmonary demand while producing high mechanical force (Lipski et al., 2018; Mater et al., 2023; Peñailillo et al., 2013) and offers a training alternative for those who may not otherwise be able to engage in regular endurance training (Douglas et al., 2017; Petrella et al., 2005; Roig et al., 2010). While beneficial changes in muscle architecture (i.e. shifts in muscle length and associated alterations in fascicle length and function) have been observed after eccentric training at the dynamometer in young healthy adults (Alonso-Fernandez et al., 2021; Leong et al., 2013) its impact on the dynamic T-V characteristics and muscle geometry of older adults has not been systematically compared to traditional concentric protocols.

To address these gaps, this study combined dynamometric and ultrasound data to investigate how 8 weeks of different workload-matched endurance training modalities—moderate-intensity continuous (CC-MOD), heavy-intensity continuous (CC-HVY), high-intensity interval training (CC-HIIT), and heavy-intensity continuous eccentric cycling (ECC)—affect muscle mechanical and architectural characteristics in older adults. These training modalities were selected because they represent distinct endurance exercise stimuli that differ in metabolic intensity, exercise structure, and contraction mode. Specifically, CC-MOD reflects the intensity typically recommended for health promotion in older adults, CC-HVY and CC-HIIT provide progressively greater physiological and neuromuscular demands, whereas ECC allows the application of high mechanical loads with a comparatively low cardiometabolic cost. Comparing these modalities at matched workload

provides a unique opportunity to isolate the influence of exercise intensity and contraction type on muscle mechanical and architectural adaptations.

We hypothesized that all cycling training modalities would significantly improve muscle function. In addition, we hypothesized that CC-HVY and CC-HIIT would be more effective in improving maximum voluntary isometric torque (T_{max}) due to the relatively higher training intensity compared to CC-MOD and ECC, and that, due to training specificity, ECC would be uniquely effective in enhancing eccentric torque (T_{ecc}). Finally, given the endurance nature and the 8-week duration of all interventions, we expected minimal, if any, changes in muscle architecture, as geometrical remodelling is more typically associated with longer-term strength training protocols.

2. Methods

2.1. Participants

Fifty healthy older adults (25 males and 25 females), recreationally active, participated in this study. Stratified randomisation based on sex and age was used to assign participants to one of four cycling exercise intervention groups ($n = 40$) or a control group (CI) ($n = 10$). The participants' anthropometric characteristics and physical activity levels, as measured by the International Physical Activity Questionnaire (IPAQ) are reported in Table 1. Subjects with neuromuscular injuries within the last six months were excluded from the study. All participants received written and oral instructions prior to the study and provided their written informed consent for the experimental procedure. The experimental protocol was approved by the Ethics Committee of the University of Verona (protocol number: #55/2025).

2.2. Experimental design, training protocols and procedures

This study employed a true-experimental research design, where participants were tested before (pre) and after (post) 8 weeks of training, with three sessions per week, resulting in 24 sessions by the end of the program. Participants in the control group were also tested 8 weeks apart; also in this case we will use the terms pre and post to indicate the two testing sessions. Exercise training was conducted Monday through Saturday, and participants were required to leave at least 24 h of recovery between subsequent sessions and at least one 48-hour rest period within each week (i.e., training three days in a row was not permitted). Training was carried out on a cyclo-ergometer (Monark, version: LC2) in concentric conditions: CC-MOD, CC-HVY and CC-HIIT, whereas ECC was performed on an eccentric cycle ergometer (Cyclus2, RBM elektronik-automation GmbH, Leipzig, Germany). The participants were requested to maintain a pedaling cadence of 65–80 bpm in all training modalities; bike fitting was based on the safety and comfort of the participants and was replicated exactly in the post test as in the pre-evaluation. For all participants and training modalities the knee and hip angles were 65–70° (top dead center, TDC) and 145–155° (bottom dead center, BDC) for the knee and between 55 and 70° (TDC) and 100–110° (BDC) for the hip. Ankle angle ranged from 100 to 120°.

These training modalities were matched for workload (kJ), calculated as power output (W) · exercise time (s) ÷ 1000. The CC-MOD group performed 50 min of cycling at 90% of the power output at the Gas Exchange Threshold (GET). This duration was chosen so that this group would meet well-established physical activity guidelines for individuals aiming to become active and/or maintain health rather than training for sport performance (Tremblay et al., 2011). The other training protocols (i.e., CC-HVY, CC-HIIT and ECC) were matched to obtain the same total work proposed for CC-MOD, according to Inglis et al. (2024): CC-HVY was performed for 35 min at 70% of the delta between the respiratory compensation point (RCP) and the GET; ECC was performed for 35 min at 70% of the delta between the RCP and the GET (the same as CC-HVY); CC-HIIT was performed in 6 blocks of 4 min at 120% of the RCP state,

Table 1

Participants' characteristics at baseline (before training); body mass data after training are reported as well. Values are means $\pm$ SD. BMI: body mass index; IPAQ: physical activity levels; CC-MOD: moderate-intensity continuous training; CC-HVY: heavy-intensity continuous training; CC-HIIT: high-intensity interval training; ECC: heavy-intensity continuous in eccentric cycling; CI = control group.

	CC-MOD (n = 10)	CC-HVY (n = 10)	CC-HIIT (n = 11)	ECC (n = 9)	CI (n = 10)
Age (years)	67.9 $\pm$ 6	65.9 $\pm$ 5.8	67.5 $\pm$ 6.3	66.2 $\pm$ 3.6	66.4 $\pm$ 3.6
Stature (cm)	170 $\pm$ 13.2	167 $\pm$ 7.1	168 $\pm$ 10.4	168 $\pm$ 7.1	169 $\pm$ 9.9
Body mass (kg) pre	77.4 $\pm$ 14.3	69.4 $\pm$ 12.4	70.3 $\pm$ 14.2	65.7 $\pm$ 11.7	66.9 $\pm$ 13.9
Body mass (kg) post	77.6 $\pm$ 14.6	69.1 $\pm$ 12.1	70.1 $\pm$ 13.8	65.8 $\pm$ 11.9	66.1 $\pm$ 13.5
BMI (kg m ⁻²)	26.8 $\pm$ 3.8	24.7 $\pm$ 3	24.6 $\pm$ 3.1	23.2 $\pm$ 2.6	23.2 $\pm$ 2.7
IPAQ (MET·min week ⁻¹)	3361 $\pm$ 1778	2816 $\pm$ 1073	3031 $\pm$ 1563	4169 $\pm$ 1930	3933 $\pm$ 3158

followed by 3 min at 30% of the GET. An example of these calculations, for a representative subject, is reported in Table 2. For this subject, power output at GET and RCP were 120 and 170 W, respectively; for CC-HIIT, the reported power and time data are the average of the two intensities (4 min at 120% of the RCP state +3 min at 30% of the GET).

During training, heart rate data were registered for each participant and in each experimental session, to control for training intensity (in terms of %HR_{max}). More details on the preliminary tests based on which RCP, GET and HR_{max} were determined are given in the supplementary materials.

To monitor training stimulus, the training impulse (TRIMP, a heart rate based method for quantifying internal training load) was also calculated for each participant and in each experimental session as proposed by Banister and Calvert (1980): TRIMP = Volume (time) · $\Delta\text{HR}^{0.64} \cdot e^{(1.92 \Delta\text{HR})}$ for males and TRIMP = Volume (time) · $\Delta\text{HR}^{0.86} \cdot e^{(1.67 \Delta\text{HR})}$ for females; where $\Delta\text{HR} = (\text{HR}_{\text{mean}} - \text{HR}_{\text{rest}}) / (\text{HR}_{\text{max}} - \text{HR}_{\text{rest}})$.

A preliminary session, which included the IPAQ and a general medical screening, was performed a few days before the tests.

During the experimental sessions (pre- and post-training), an ultrasound apparatus was used to acquire the vastus lateralis (VL) geometrical properties at rest. After that, each participant performed a series of maximum isometric and isokinetic contractions to reconstruct the T-A and T-V relationships.

2.3. Testing protocols

The participants were secured on a dynamometer (Cybex HUMAC Norm, USA) using a pelvic and trunk Velcro strap, with their arms crossed in front of their chest. The dynamometer and the knee axis of rotation were aligned at 90° of knee flexion during a maximal voluntary isometric contraction to ensure alignment during contraction (Bakenecker et al., 2019).

The VL geometry was recorded using an ultrasound apparatus (MicrUs EXT1H, Telemed UAB, Vilnius, Lithuania) with a linear transducer (65 mm, 4–8 MHz, LV8-4L65 S3, Telemed UAB, Vilnius, Lithuania). Ultrasound setting was individually adjusted to provide the clearest possible image; the sample frequency was 35 Hz. The probe was placed in the middle of the muscle belly (approximately 50% of the femur length, measured from the great trochanter to the upper part of the patella). The probe was aligned along the longitudinal axis of the

Table 2

Training modalities were matched for workload (kJ), calculated as power output (W) · exercise time (s) ÷ 1000. This table reports an example of these calculations for a representative subject (see Methods for details). CC-MOD: moderate-intensity continuous training; CC-HVY: heavy-intensity continuous training; CC-HIIT: high-intensity interval training; ECC: heavy-intensity continuous in eccentric cycling.

	Power (W)	Time (min)	Workload (kJ)
CC-MOD	108	50	5.4
CC-HVY	155	35	5.4
CC-HIIT	132	41	5.4
ECC	155	35	5.4

muscle belly and adjusted to obtain a clear image of the perimysial connective tissue within the muscle.

After a warm-up based on sub-maximal fixed-end and iso-velocity contractions (45, 90, 150, 210, 250°/s), resting muscle geometry of the VL was collected, with the participants positioned with a knee joint angle of 75°. We adopted this specific angle because it is close to the optimal knee joint angle, as reported by Lanza et al. (2019). Subsequently, each participant performed two maximum voluntary isometric contractions at five different knee joint angles (90, 75, 60, 45, and 30°) and two maximum isokinetic concentric and eccentric contractions at five different knee angular velocities (45, 90, 150, 210, and 250°·s⁻¹). A period of 90 s of rest was maintained between contractions to prevent muscle fatigability. During the isometric contractions, the participants were instructed to reach the maximum torque gradually (3–4 s). In contrast, during the isokinetic contractions, the participants were asked to push “as hard as possible” over the entire range of motion.

Torque, angular velocity, and angular position were recorded simultaneously using an analogue-digital converter (Quattrocento, OTBioelettronica, Turin, Italy); the ultrasound trigger (square wave pulses) was utilized to synchronise the apparatuses.

2.4. Data analysis

Muscle geometry at rest was evaluated, and three frames were tracked approximately 1 s before contraction (ImageJ v.1.54p): muscle thickness was defined as the distance between the superficial and deep aponeurosis; pennation angle was defined as the angle formed by the insertion of the fascicle within the deep aponeurosis; fascicle length was calculated by dividing muscle thickness by the sine of the pennation angle (Van Hooren et al., 2024).

The total torque generated by the knee extensors was corrected for the effect of gravitational torque as determined during a passive joint rotation driven by the dynamometer (Hauraix et al., 2017). The torque value reached during the steady state of the two maximum voluntary isometric contractions was averaged, and these data were used to reconstruct the T-A relationship by fitting the torque values obtained at each knee angle with a cubic spline. T_{max} and K_{Aopt} were calculated as the apex of the T-A relationship and the corresponding joint angle, respectively (Anderson et al., 2007).

The maximum torque reached during the isokinetic phase for each concentric and eccentric contraction was then determined (e.g. the acceleration and deceleration phases were not considered). The maximum torque generated during all isokinetic eccentric contractions was fitted with a linear equation, and the intercept on the y-axis was used as the maximum T_{ECC}. Torque-angular velocity data in concentric conditions were fitted with the Hill equation ((T0·b)/a) (Cailliet et al., 2022), and the intercepts on the x and y axes were interpreted as the V_{max} and T_{max}, respectively.

In Fig. 1, a typical concentric-eccentric isokinetic contraction at 90°/s (top panel, left) and a typical torque-time curve during a maximal voluntary isometric contraction at 90° knee angle (top panel, right) are reported for a representative participant. In the bottom panels, the data points utilized to reconstruct the T-V relationship (left) and the T-A relationship (right) are reported as well, for the same participant.

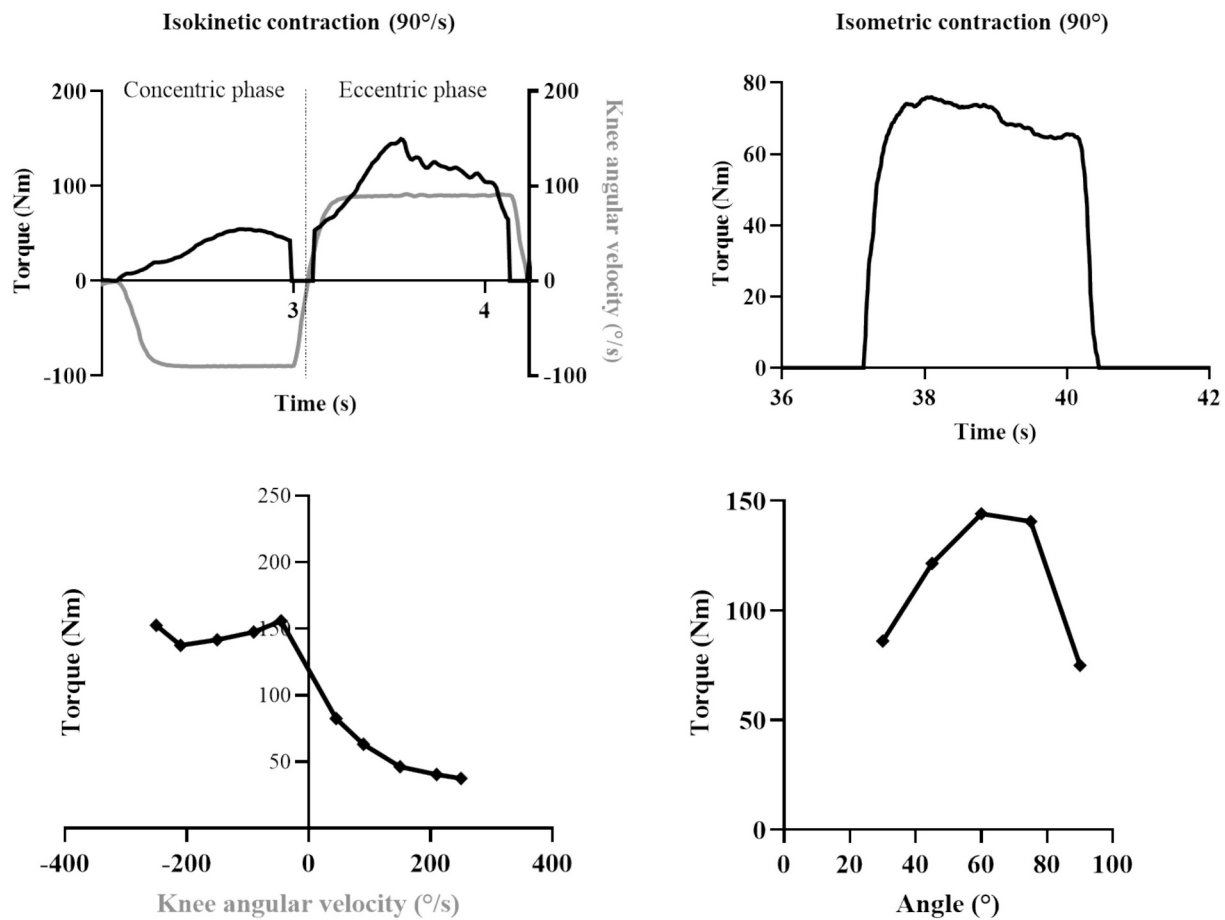


Fig. 1. An isokinetic concentric and eccentric contraction at 90°/s (top panel, left) in a representative participant, and the data points utilized to reconstruct the T-V relationship (bottom panel, left); a maximum voluntary isometric contraction at 90° knee angle (top panel, right) and the data points utilized to reconstruct the T-A relationship (bottom panel, right) in the same participant.

The group average T-A and T-V data points for the four training groups and the control group pre and post training are reported in the supplementary materials.

2.5. Statistics

All data are presented as mean $\pm$ SD. A one-way ANOVA (Fisher) was used to compare the participants' characteristics at baseline. A two-way (Group $\cdot$ Time) repeated measures ANOVA was used to evaluate the effects of time (pre-post), group (four training groups and the control group), and the possible interaction. Where significant effects were found, Tukey-adjusted post-hoc comparisons were conducted. To quantify the magnitude of the impact in the repeated-measures ANOVA, partial eta squared (η_p^2) was used as the effect size index. Following conventional benchmarks for η_p^2 , values of 0.01, 0.06, and 0.14 were interpreted as small, medium, and large effects, respectively (Cohen, 2009; Richardson, 2011). Residual plots were examined to verify assumptions of normality and homoscedasticity in all variables. The level of significance was set at $p < 0.05$. Statistical analyses were performed using Jamovi (version 2.6.44).

Mixed repeated measures ANOVAs (Time $\cdot$ Angle $\cdot$ Group for the T-A relationships and Time $\cdot$ Angular Velocity $\cdot$ Group for the T-V relationships) were also performed, their results are reported in the supplementary materials.

3. Results

No differences in age, stature, body mass, body mass index and IPAQ

were observed among groups at baseline (one way ANOVA). No changes in body mass were observed after training in all groups (paired t -test).

Training intensity expressed as %HRmax was similar among concentric training modalities (CC-MOD: $69.9 \pm 8.8\%$; CC-HVY: $77.0 \pm 5.9\%$; CC-HIIT: $79.6 \pm 5.2\%$) but %HR values were systematically lower in ECC ($57.2 \pm 6.4\%$). Similarly, no differences were observed in training impulse (TRIMP) among concentric training modalities (CC-MOD: $113.8 \pm 19.8\%$; CC-HVY: $103.6 \pm 30.0\%$; CC-HIIT: $115.5 \pm 25.6\%$) but TRIMP values were systematically lower in ECC ($50.7 \pm 7.8\%$).

Training adherence across all intervention groups was $96.2 \pm 2.2\%$.

3.1. Muscle architecture

No statistically significant differences were detected in VL muscle thickness, pennation angle and fascicle length among groups at baseline (all: $p > 0.05$).

The average ($\pm$ SD) values of the muscle architectural characteristics pre and post training are reported in Fig. 2. No statistically significant differences were detected in muscle thickness, pennation angle and fascicle length as a function of time in all groups (main effect of time and group: $p > 0.2$ and $\eta_p^2 < 0.01$).

Although the time-group interaction reached significance for muscle thickness, the effect size was small ($p = 0.048$, $\eta_p^2 = 0.188$) and post-hoc tests did not identify specific group differences.

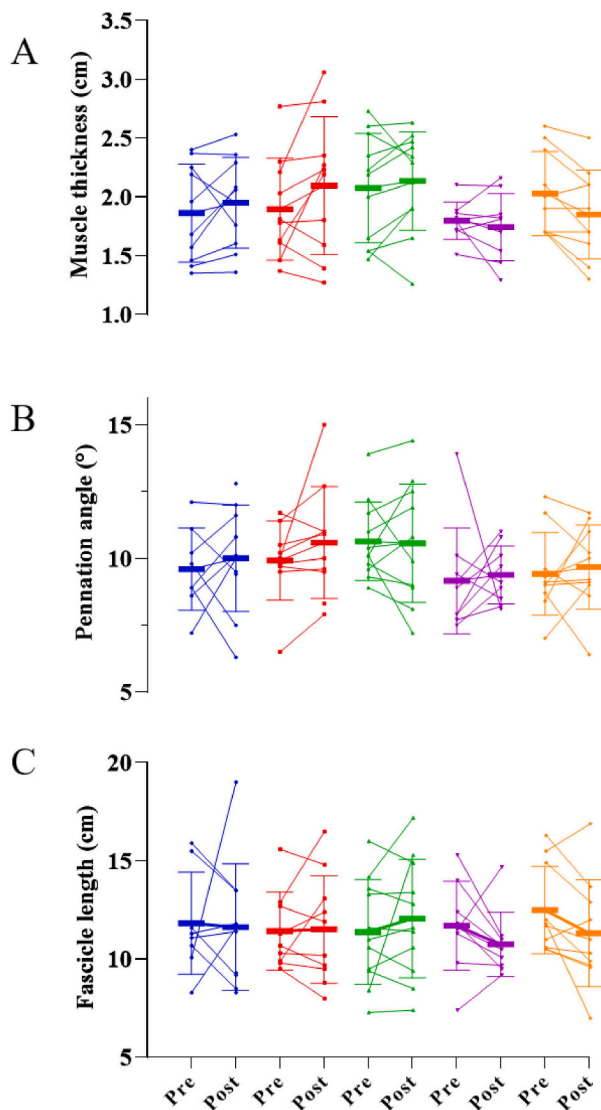


Fig. 2. Muscle thickness (panel A), pennation angle (panel B) and fascicle length (panel C) before (pre) and after (post) training in CC-MOD (blue), CC-HVY (red), CC-HIIT (green), ECC (purple) and CI (orange). Values are means $\pm$ SD, individual data are represented as well. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

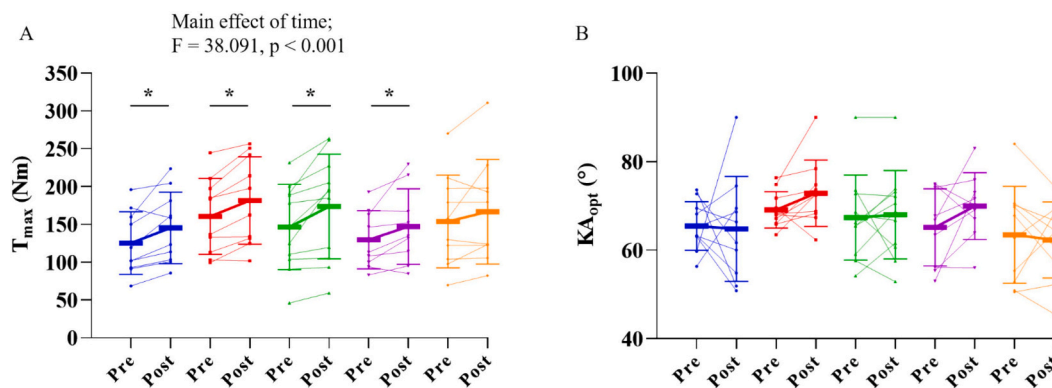


Fig. 3. T_{max} (panel A) and KA_{opt} (panel B) before (pre) and after (post) training in CC-MOD (blue), CC-HVY (red), CC-HIIT (green), ECC (purple) and CI (orange). Values are means $\pm$ SD, individual data are represented as well. *: $p < 0.05$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Torque-angle relationship

No statistically significant differences were detected in T_{max} and KA_{opt} among groups at baseline (all: $p > 0.05$). The average ($\pm$ SD) values of T_{max} and KA_{opt} pre and post are reported in Fig. 3. No significant effect of group and time (and no group-time interaction) was observed for the optimal knee angle.

A main effect of time ($p < 0.001$; $\eta_p^2 = 0.458$) was observed for T_{max} indicating a medium increase from pre to post. The main effect of group and the group-time interaction were not significant; however, post hoc tests (within-group comparisons) indicate a robust pre-post increase in the training groups (CC-MOD: $p = 0.007$; $\eta_p^2 = 0.23$; CC-HVY: $p = 0.005$; $\eta_p^2 = 0.31$; CC-HIIT: $p < 0.001$; $\eta_p^2 = 0.44$; ECC: $p = 0.025$; $\eta_p^2 = 0.37$) and no changes in the control group (CI: $p = 0.078$; $\eta_p^2 < 0.001$).

3.3. Torque-velocity relationship

No statistically significant differences were detected at baseline for T_{ecc} and V_{max} in all groups (all: $p > 0.05$). The average ($\pm$ SD) values of T_{ecc} and V_{max} pre and post are reported in Fig. 4. No significant effect of group and time (and no group-time interaction) was observed for the V_{max} .

A low, yet significant, main effect of time ($p = 0.002$; $\eta_p^2 = 0.191$) was observed for T_{ecc} , whereas no main effect of group and no group-time interaction were observed ($p > 0.6$ and $\eta_p^2 < 0.06$). Post hoc analyses confirmed a significant difference between pre and post measurements ($p = 0.002$), with no differences within groups.

Additional analyses of the T-V and T-A relationships showed no group-specific adaptations: overall, concentric torque remained unchanged, whereas eccentric torque and torque across joint angles increased from pre to post test, with similar adaptations across groups (see Supplementary Materials for further details).

4. Discussion

This study investigated the effects of three commonly utilized concentric and one eccentric cycling endurance training protocols, matched for workload, on the mechanical and architectural responses of the muscle in older adults after 8 weeks of training.

Work-matched concentric cycling training protocols and eccentric cycling training are all associated with a significant improvement in T_{max} or T_{ecc} after 8 weeks (i.e. a significant main effect of time). However, contrary to our hypothesis, we did not detect statistically significant differences among the concentric cycling protocols of variable intensity or the eccentric cycling training protocol. This suggests that, over an 8-week training period, differences in endurance training intensity, volume, or exercise modality have minimal impact on muscle

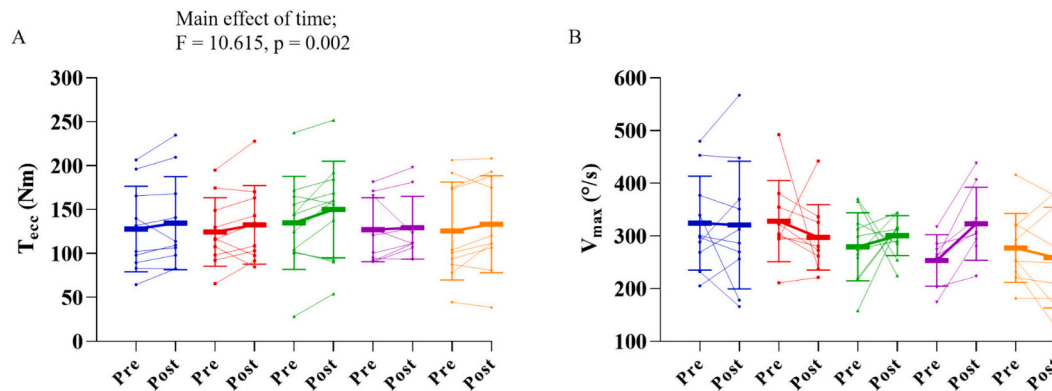


Fig. 4. T_{ecc} and V_{max} before (pre) and after (post) training in CC-MOD (blue), CC-HVY (red), CC-HIIT (green), ECC (purple) and CI (orange). Values are means $\pm$ SD, individual data are represented as well. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mechanical adaptations when total work performed is matched. Moreover, no statistically significant differences were detected in V_{max} and KA_{opt} over time or group. Finally, in agreement with our second hypothesis, we did not observe significant differences in VL muscle architecture as a function of training modalities and training time.

4.1. Training load in concentric and eccentric conditions

Training modalities were matched for total workload, and exercise intensity was prescribed according to metabolic criteria rather than mechanical loading. The rationale of selecting these specific modalities was to investigate whether differences in exercise intensity (physiological response), exercise structure (continuous vs. interval), and contraction mode (concentric vs. eccentric) independently influence muscle mechanical and architectural adaptations in older adults.

Actual exercise intensity during training was similar in the concentric modalities (70–80% HR_{max}) and significantly lower in the eccentric one (about 55% HR_{max}). Nevertheless, all modalities equally improved T_{max} and T_{ecc} ; e.g. eccentric cycling training produces mechanical adaptations similar to those obtained with concentric cycling training, despite a lower metabolic effort.

It must be pointed out that a given metabolic intensity (e.g. 80% of GET) may not reflect an equivalent percentage of the maximal force-producing capacity of the quadriceps. Consequently, the actual mechanical stimulus applied to the knee extensors during eccentric training may have been relatively low, potentially limiting hypertrophic and architectural adaptations typically associated with higher mechanical loading (Leong et al., 2013). Indeed, the superior strength gains often attributed to eccentric exercise are usually observed when the eccentric modality is used to impose a higher mechanical load than concentric exercise, taking advantage of the lower metabolic and cardiopulmonary cost of eccentric contractions. In contrast, when eccentric and concentric cycling are matched for external workload, as in our case, the eccentric condition may retain a lower cardiopulmonary and perceptual demand, without necessarily providing a greater mechanical stimulus to the knee extensors. Therefore, the workload-matched, submaximal, endurance-based nature of the protocol may have contributed to the absence of superior strength gains following eccentric cycling. However, because force production during pedaling, muscle activation and internal mechanical loading were not directly assessed in this study, this interpretation remains speculative.

4.2. Muscle architecture

Our results showed no significant changes in either VL fascicle length or KA_{opt} after 8 weeks of different work-matched endurance concentric cycling training (and neither in eccentric training) in older adults. Compared to the studies that have observed changes in muscle

architecture following concentric cycling endurance training (Bruseghini et al., 2019), our intervention may have not been sufficiently prolonged (2 vs 3–6 months) for such changes to manifest. Moreover, the relatively high initial activity level of the older adults in our study (an IPAQ score of about 3000 MET·min·week⁻¹ corresponds to a high physical activity level) may at least partially explain the lack of observed changes in muscle architecture in our study. Significant increases in muscle length and associated alterations in fascicle length have previously been demonstrated following eccentric knee extension training, particularly in young healthy adults (Baroni et al., 2013). Compared to eccentric knee extension, our eccentric cycling training, designed to be work-matched with concentric cycling protocols, may have been insufficiently strenuous to produce measurable changes.

In summary, the present study suggests that 8 weeks of different, work-matched endurance training modalities do not affect muscle architecture in healthy, active, older adults of both sexes. Our findings also imply that the observed differences in muscle mechanical output after endurance training could not be attributable to changes in muscle architecture.

4.3. Torque-angle relationship

The T-A relationship is particularly sensitive to training-induced functional adaptations or altered mechanical demands (Bertoli et al., 2019; Wisdich et al., 2025). In addition, age-related changes such as reduced tendon stiffness and sarcopenia alter muscle architecture and mechanics, leading to a shift in the T-A relationship (Narici et al., 2008). This shift typically results in a decreased range of motion and reduced force production at specific joint angles, thereby contributing to declines in physical function and strength observed in older adults (Ateş et al., 2023; Cameron et al., 2023; Hagen et al., 2015). Significant shifts in muscle length and associated alterations in fascicle length have previously been demonstrated following eccentric and concentric knee extension training, particularly in young healthy adults (Benford et al., 2021). Studies have shown that eccentric training, in particular, tends to increase fascicle length and alter muscle architecture to a greater extent than concentric training (Baroni et al., 2013). In line with these findings, our results showed no significant changes in either fascicle length or KA_{opt} within our study cohort.

We observed an increase in T_{max} after endurance training in all the investigated training groups, suggesting an upward shift of the T-A relationship. Similar results were reported by Sipilä et al. (1996) and Burich et al. (2015), who observed an increase in knee extensor torque after 9 weeks of endurance training in older adult participants. However, there was no interaction effect between time and training protocol, indicating that both the training intensity and type were less influential in enhancing isometric strength than the act of training itself (Cadore et al., 2013). Interestingly, while eccentric endurance cycling involves

a lower metabolic and cardiovascular demand than concentric exercises when matched for workload, the increase in $T_{\max}$ relative to the baseline values is similar in older adults. Notably, no differences in $T_{\max}$ were observed in the control group.

In agreement with our data, [Lewis et al. \(2018\)](#) investigated muscle strength adaptations in sedentary middle-aged males after 8 weeks (2 sessions per week) of concentric and eccentric cycling at the same workload (60% of peak power output) and observed that both eccentric and concentric training elicited a significant increase in $T_{\max}$, with no between group differences, despite the eccentric protocol elicited markedly lower heart rate and perceived exertion. In summary, our results indicate that both concentric and eccentric cycling training when matched for workload are helpful in improving maximum isometric strength in older adults.

4.4. Torque-velocity relationship

This is the first study to investigate the T-V in older adults following different endurance training protocols.

Ageing typically reduces torque-generating capacity across the T-V relationship, but the decline appears greatest for concentric actions ([Hortobágyi et al., 1995](#); [Pousson et al., 2001](#)). Indeed, older adults show a relatively preserved capacity to produce eccentric strength ([Roig et al., 2010](#)). Potential mechanisms for preserving eccentric strength in older adults are neurological, mechanical and cellular ([Roig et al., 2010](#)). The neurological mechanisms are: i) decreased agonist activation ([Bigland and Lippold, 1954](#)) and ii) increased antagonist activation ([Kellis and Baltzopoulos, 1999](#)). The mechanical mechanisms are: i) increased connective tissue ([Alnaqeeb et al., 1984](#)) and ii) increased muscle passive stiffness ([Ochala et al., 2004](#)). The cellular mechanisms are: i) preserved tension in old muscle fibres during stretch ([Armstrong et al., 1991](#)) and ii) increased instantaneous stiffness in old muscle fibres ([Valour and Pousson, 2003](#)). Different methods to reverse these changes have been investigated, including traditional, power, and eccentric (or eccentrically biased) resistance training.

We found an increase in T_{ecc} after training, with no differences between groups and no differences in the $V_{\max}$. Increased eccentric strength without architectural remodelling may reflect improved neural activation and, possibly, changes in tendon stiffness/elastic components ([Kubo et al., 2007](#)), but these factors were not directly investigated in this study. Another possible explanation for the increase of T_{ecc} in all groups could be attributed to habituation; indeed, performing eccentric contractions at the dynamometer requires more familiarization than concentric contractions and the observed increase in T_{ecc} , rather than to training per se, could be the effect of an increased habituation to the experimental procedures (e.g. to a learning effect, indeed observed also in the control group).

According to the review by [Raj et al. \(2010\)](#), older adults exhibit a reduced $V_{\max}$ compared to younger adults, which is likely due to a combination of factors, including changes in muscle fibre type and muscle architecture. Muscle fascicle length and pennation angle are routinely reported to be lower in older than in young adults ([Morse et al., 2005](#); [Narici et al., 2003](#); [Thom et al., 2007](#)). Shorter muscle fascicles in older adults generate force over a smaller range of motion and exhibit reduced maximum shortening speeds compared to those of younger adults ([Blazevich and Sharp, 2005](#)). [Narici et al. \(2003\)](#) found that muscle fascicle length was about 10% smaller in older males compared to young males, which contributed to the age-related decline in $V_{\max}$. [Thom et al. \(2007\)](#) demonstrated that approximately 22% of the age-related decline in $V_{\max}$ is attributable to shorter fascicle lengths in older adults. Shorter fascicles also have higher sarcomere shortening rates, which further reduces the force generated at any given contraction velocity ([Blazevich and Sharp, 2005](#)). We observed no differences in $V_{\max}$ after training in all groups, and this could be due to the absence of morphological changes (muscle geometry) as well.

5. Limitations

The sample size per group (9–11 subjects) was rather small, which reduced the statistical power to detect differences between modalities.

Although the VL is regarded as a primary knee extensor due to its sizeable cross-sectional area, the other quadriceps compartments also contribute to the knee extensor moment ([Narici et al., 1989](#)). Therefore, potential adaptations occurring in other muscles, as well as changes in dynamic muscle behaviour, cannot be excluded. We did not collect neural activation pre and post training; therefore, the neurophysiological mechanisms underlying the changes in muscle strength could not be identified.

Our participants were generally active at baseline, which may have reduced the magnitude of the training-induced adaptations. Moreover, the intervention lasted only eight weeks, which may have been insufficient to induce measurable structural remodelling of skeletal muscle in active people. Longer training studies with sedentary individuals could better elucidate the impact of cycling training intensity on muscle geometrical adaptations.

The study included multiple training groups and outcome variables to provide a comprehensive assessment of the mechanical and architectural responses to different endurance training modalities. Although this is not a problem for the primary outcomes (i.e., $T_{\max}$ and $V_{\max}$), the number of statistical comparisons performed may increase the risk of type I error and should therefore be considered when interpreting secondary findings.

6. Conclusion

Work-matched endurance training protocols performed with different types of exercise (concentric vs eccentric cycling for a total of 8 weeks) enhance muscle function in older adults, even without peripheral muscle architectural adaptations. All training interventions were associated with improvements in the muscle mechanical properties that are relevant for maintaining independence and for reducing the risk of functional decline. Interestingly, eccentric cycling training appears to produce mechanical adaptations similar to those obtained with concentric cycling training despite a lower metabolic effort.

Ethics committee approval

All participants received written and oral instructions prior to the study and provided their written informed consent for the experimental procedure. The experimental protocol was approved by the Ethics Committee of the University of Verona (protocol number: #55/2025).

CRediT authorship contribution statement

Michele Trinchì: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Samuel D'Emanuele:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Andrea Monte:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Data curation, Conceptualization. **Michael Daini:** Writing – review & editing, Software, Funding acquisition. **Gianluca Boicchio:** Writing – review & editing, Software, Methodology, Investigation. **Laura Ghiotto:** Writing – review & editing, Investigation, Formal analysis. **Cantor Tarperi:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization. **Silvia Pogliaghi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Paola Zamparo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition,

Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.exger.2026.113248>.

Data availability

Data will be made available on request.

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