



Is the joint-angle specificity of isometric resistance training real? And if so, does it have a neural basis?

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Abstract

Purpose There are suggestions that isometric resistance training (RT) produces highly angle-specific changes in strength with the greatest changes at the training angle, but these effects remain controversial with limited rigorous evidence, and the possible underpinning physiological mechanism(s) remain opaque. This study investigated the extent of angle-specific changes in strength and neuromuscular activation after RT in comparison to a control group.

Methods A RT group ($n = 13$) performed 14 isometric RT sessions at a knee-joint angle of 65° (0° is anatomical position) over a 4-week period, whilst a control group (CON, $n = 9$) maintained their habitual activity. Pre- and post-test sessions involved voluntary and evoked isometric knee extension contractions at five knee-joint angles (35° , 50° , 65° , 80° and 95°), while electromyography was recorded.

Results RT group increased maximum voluntary torque (MVT) at the training angle (65° ; +12%) as well as 80° (+7%), 50° (+11%) and 35° (+5%). Joint-angle specificity was demonstrated within the RT group (MVT increased more at some angles vs. others), and also by more rigorous between-group comparisons (i.e., larger improvements after RT vs. CON at some angles than others). For the RT group, normalized EMG increased at three of the same joint angles as strength, but not for CON. Importantly, however, neither within- or between-group analyses provided evidence of joint angle-specific changes in activation.

Conclusion In conclusion, this study provides robust evidence for joint angle-specific strength gains after isometric RT, with weaker evidence that changes in neuromuscular activation may contribute to these adaptations.

Keywords Neuromuscular activation · Muscle contractile properties · Torque production · Angle specificity

Abbreviations

CON	Control group
CV_W	Within-participant coefficient of variation
ECT	Explosive contraction training
EMG	Electromyography
EVC	Explosive voluntary contraction
M_{MAX}	Supramaximal muscle compound action potential
M_{MAX} P-P	M_{MAX} peak-to-peak amplitude
MVC	Maximum voluntary contraction

MVT	Maximum voluntary torque
Octet PT	Octet peak torque
Octet T_{50}	Octet torque measure at 50 ms after torque onset
$QEMG_{0-50}$	Quadriceps femoris EMG epoch between 0 and 50 ms after EMG onset
$QEMG_{0-100}$	Quadriceps femoris EMG epoch between 0 and 100 ms after EMG onset
$QEMG_{0-150}$	Quadriceps femoris EMG epoch between 0 and 150 ms after EMG onset
$QEMG_{MVT}$	Quadriceps femoris EMG at maximum voluntary torque
RF	Rectus femoris
RT	Resistance training
SCT	Sustained contraction training
T_{50}	Explosive torque at 50 ms after torque onset
T_{100}	Explosive torque at 100 ms after torque onset

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T_{150}	Explosive torque at 150 ms after torque onset
Twitch PT	Twitch peak torque
Twitch T_{50}	Twitch torque measure at 50 ms after torque onset
VL	Vastus lateralis
VM	Vastus medialis

Introduction

Regular resistance training (RT) is widely recommended to improve muscle function (Folland and Williams 2007) and maintain musculoskeletal health (Morganti et al. 1995). Isometric RT and, in particular, sustained contraction training at high force (SCT, ≥ 2 s duration; $> 70\%$ maximum force) and at one specific joint angle may result in highly angle-specific changes in strength with the greatest changes at the training angle (Thepaut-Mathieu et al. 1988; Weir et al. 1995; Noorkoiv et al. 2014; Lum and Barbosa 2019). However, evidence for these effects remains controversial with previous studies of the knee extensors reporting a spectrum of responses from increases in strength only at the training angle [i.e., suggestive of angle-specific changes; (Gardner 1963)] through to increases at the training angle and some, but not all other angles [suggesting limited angle specificity; (Weir et al. 1995; Noorkoiv et al. 2014; Alegre et al. 2014)] and increases at all measured angles [no angle specificity (Kubo et al. 2006)]. Importantly, rigorous demonstration of angle specificity effects requires not just changes at some angles and not others, but quantitative differences in joint-angle responses (e.g., greater changes at one angle compared to another), although few studies have made these careful comparisons. In addition, use of a control group, which appears necessary to isolate the influence of a RT intervention from other potentially confounding factors [e.g., learning to perform the test (Kinser and Robins 2013), or measurement issues such as imperfect calibration or imprecise replication of the joint positions], has been included in just two studies, but without rigorous between-group statistical comparisons (Gardner 1963; Weir et al. 1995). Therefore, robust statistical evidence for isometric RT producing changes in strength that are specific to the training angle (e.g., training angle vs. other angles) and the training intervention (e.g., RT vs. control group), and thus ultimately a group \times angle interaction effect are lacking. Hence, use of a control group and appropriate statistical procedures are necessary to fully assess whether joint-angle specificity and the adaptations induced by isometric RT are genuine systematic effects.

The adaptations to short-term RT are typically ascribed primarily to neural adaptations, including increased neuromuscular activation of the agonist muscle (Gabriel et al.

2006; Folland and Williams 2007), and this has been proposed to be the mechanistic explanation for angle-specific adaptations (Thepaut-Mathieu et al. 1988; Kitai and Sale 1989; Kubo et al. 2006; Noorkoiv et al. 2014). Similar to the disparate findings for joint angle-specific torque changes after RT, neuromuscular activation has been assessed with surface electromyography (sEMG) and reported to: increase at a wide range of angles [up to 60° from the training angle (Kubo et al. 2006)]; increase for some but not all angles proximal to the training angle [i.e., within 20° of the training angle (Noorkoiv et al. 2014)]; and to remain unchanged at the training angle (Gardner 1963; Weir et al. 1995; Ullrich et al. 2009). Therefore, whether increases in agonist neuromuscular activation underpin joint angle-specific strength increases after short-term SCT remains unclear. These contrasting findings may be due to a lack of contemporary sEMG methods such as joint angle-specific *M*-wave normalization (Lanza et al. 2017), duplicate sensors on each superficial constituent muscle (Balshaw et al. 2017), and duplicate measurement sessions at each timepoint (i.e., pre- and post-training) to enhance measurement reliability.

The ability to produce torque as quickly as possible from a low/resting level, known as explosive torque, is important for explosive athletic performance (Paasuke et al. 2001; Tillin et al. 2013a), but also appears to be critical to recovering from a loss of balance and thus, fall prevention (Izquierdo et al. 1999; Pijnappels et al. 2008; Behan et al. 2018). Previous research has shown marked training/contraction-specific adaptations, such that explosive-contraction training (ECT), but not SCT, are effective at increasing early phase explosive torque [≤ 100 ms after contraction onset (Tillin and Folland 2014; Balshaw et al. 2016)]. However, it is unknown if the addition of explosive-contractions to SCT may facilitate a broader range of adaptations with increases in both maximal and explosive strengths.

Therefore, the primary aim of this study was to examine the extent of angle-specific changes in strength after RT (i.e., greater increases at the training angle and in comparison, to a control group), and whether changes in neuromuscular activation might explain any angle-specific strength changes. We hypothesized that the training intervention would increase strength at the training angle (65°) by more than the outermost angles (35° and 95°) and in comparison to a control group (i.e., group \times angle interaction), and that this would be explained by increases in neuromuscular activation. The secondary aim was to investigate if the addition of ECT to SCT facilitated improvements in early phase explosive strength, as well as the expected increases in maximum strength.

Methods

Participants

Twenty-two recreationally active males with no previous major lower body injuries or systematic lower body RT for at least 12 months were recruited and randomly assigned to either a RT ($n = 13$; age, 22 ± 3 years; height, 1.78 ± 0.07 m; body mass, 73 ± 7 kg) or control group (CON; $n = 9$; age, 23 ± 3 years; height, 1.79 ± 0.08 m; body mass, 75 ± 8 kg) and completed this study. The sample size of the present study was estimated from the improvements in maximum voluntary torque (MVT) during previous isometric RT studies (Tillin and Folland 2014; Balshaw et al. 2016; Noorkoiv et al. 2014) to calculate Cohen's d effect size (ES; Cohen 1988) for the greater improvement at the training angle than the most extended angle in the RT vs CON groups ($ES = 1.47$). Power analysis was then used to estimate sample size with an alpha of 0.05 and a statistical power of 80%, and revealed eight participants per group would be required to detect these effects. Ethical approval was granted by the Loughborough University Human Participants Sub-Committee and participants provided written informed consent prior to their participation according to the principles of The Declaration of Helsinki.

Overview

All training and testing of the knee extensors (unilateral contractions of the dominant leg) were performed at a consistent time of the day with participants seated and strapped to an adjustable custom-made isometric testing chair at a constant hip-joint angle of 70° (0° is the anatomical position). Participants first visited the laboratory for a familiarization session involving extensive practice of the voluntary contractions at the full range of angles, and experience with evoked twitch contractions. After familiarization, two duplicate laboratory measurement sessions were conducted both pre and post the 4-week intervention period (i.e., four measurement sessions in total). Pre-measurement sessions occurred 3–7 days apart prior to the first training session and post-measurement sessions were performed 3 days after the last training session and then, 2–3 days later. Each measurement session involved isometric knee extension contractions [maximum voluntary contractions (MVC), explosive voluntary contractions (EVC)], and evoked twitch contractions at five different knee-joint angles [35° , 50° , 65° , 80° and 95° (where 0° is anatomical position)]. Joint angles were tested in an opposite and counterbalanced order (Fig. 1) during both pre- and post-measurement sessions. Torque and superficial quadriceps

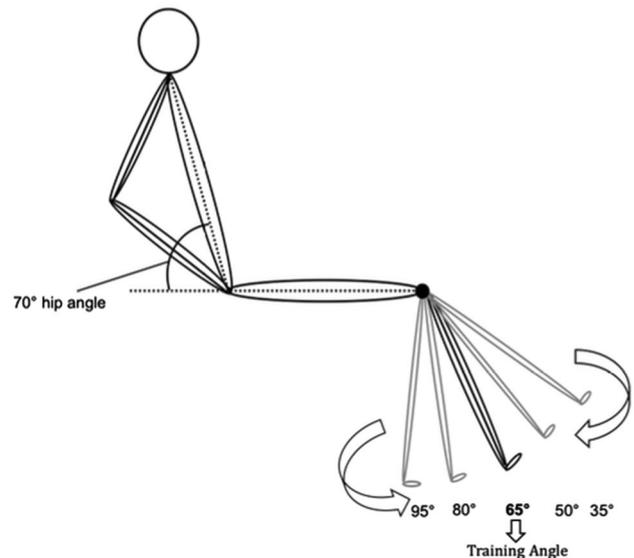


Fig. 1 A schematic of the hip and knee angles during the maximum, explosive, and evoked knee extension contractions performed during the testing sessions and the training angle used during the training sessions. Arrows indicate ascending and descending order which the participant performed the tasks in a counterbalanced order within pre- and post-test sessions. If during the first test session, the participant performed the task in a descending order, for the next test session, a descending order was performed

femoris EMG [vastus lateralis (VL), vastus medialis (VM) and rectus femoris (RF)] were recorded during maximum and explosive contractions, as well as evoked twitch contractions. Two octet contractions [eight pulses at 300 Hz; known to drive the muscle at its maximum ability to produce explosive torque for ~ 50 ms (de Ruiter et al. 2004)] were also evoked at each angle during one pre- and one post-measurement session. The RT group completed 14 training sessions in 4 weeks ($\times 3/\text{week}$ for 2 weeks and then $\times 4/\text{week}$ for 2 weeks) at a 65° knee-joint angle, and each session involved a combination of ECT and SCT. The RT and CON groups were instructed to continue with their habitual physical activity and lifestyle, and CON only attended the pre- and post-measurement sessions.

Training

A brief warm-up of sub-maximum contractions [50% ($3\times$), 75% ($2\times$), and 90% ($1\times$)] was performed before each RT session. Within each individual training session, participants completed ECT (three sets of ten repetitions with 10 s between contractions; ~ 1 min per set) followed by SCT (three sets of six repetitions with 30 s between contractions; ~ 3 min per set) of their dominant leg, with 2-min rest between each set and approximately 25 min per session. For the ECT repetitions, participants were instructed to perform each contraction “as fast and hard as possible” up to $\geq 80\%$

of MVT for ~ 1 s, and then relax for 5 s between repetitions. A computer monitor was used to display peak rate of torque development (10-ms time epoch) to provide biofeedback of explosive performance. The torque–time curve was also shown: with a horizontal cursor at 80% MVT to ensure sufficiently forceful contractions; on a sensitive scale highlighting baseline torque to observe and correct any pre-tension or countermovement. For SCT, each contraction was an MVC and participants were instructed to “push as hard and fast as possible” for 3 s with 20 s rest between contractions. During the MVCs, a computer monitor was used to display a target torque trace 4 s before every contraction and participants were instructed to exceed the horizontal target line (i.e., the maximum torque achieved until that session) and verbal encouragement was provided. During each training session, the highest torque value achieved during an MVC at any point during the intervention up until that point (i.e., measurement or training session) was used to prescribe both ECT and SCT repetitions.

Torque, surface EMG and video recording

Participants were seated on an adjustable custom-made isometric knee extension dynamometer (Maffiuletti et al. 2016; Fig. 6b), with straps across the chest and waist to reduce extraneous body movement. This dynamometer is highly rigid with no padding and tight inextensible straps, and thus affords minimal movement between rest and MVC. The dynamometer configuration was established for each participant during familiarisation, and the actual knee joint angles at each position were assessed during this session with sagittal plane video images of the leg recorded during MVCs using a video camera placed lateral to the participant (Panasonic HC-V110, Secaucus, New Jersey, USA). Knee-joint angle was determined as the angle between visible markers placed on the greater trochanter, lateral knee-joint space and lateral malleolus by digitising the video images using freely available public domain analysis software (Kinovea 0.8.15).

Force was measured with a calibrated S-beam strain-gauge (linear range 0–1500 N, Force Logic, Swallowfield, UK) which was attached perpendicular and posterior to the tibia with a reinforced inextensible webbing strap (35 mm width) fastened ~ 3 cm superior to the lateral malleolus. Force was sampled and recorded at 2000 Hz using an analogue-to-digital converter (A/D Micro 1401, CED, Cambridge, UK) and a computer utilising Spike 2 software (CED, Cambridge, UK). A 50 Hz notch filter with an infinite impulse response digital filter (q -factor of 10) was used to remove main frequency noise and the force signal was also low-pass filtered at 500 Hz with a fourth-order zero-lag Butterworth digital filter. Torque was calculated as the product of force (after gravity correction by subtracting baseline

force) and lever arm length (the distance between the knee-joint centre and the middle of the strap).

sEMG was recorded during pre- and post-measurement sessions with a wireless EMG system (Trigno; Delsys, Inc., Boston, MA, USA). After shaving, abrading, and cleansing with 70% ethanol (standard preparation of the skin), single differential sensors (Delsys Inc., Boston, MA, USA) were attached at six sites over the superficial quadriceps muscles using adhesive interfaces. sEMG sensors were located at the following percentages of thigh length (the distance from the knee-joint centre to the greater trochanter) above the superior border of the patella over the VM (25 and 35%), VL (50 and 60%) and RF (55 and 65%). EMG signals were amplified and filtered at source (300 \times ; 20–450-Hz bandwidth) before further amplification (overall effective gain, 909 \times) and subsequently sampled at 2000 Hz using the same external A/D converter and computer software as the torque recordings. During the offline analysis, the sEMG data were time aligned with the torque signal due to an inherent 48-ms delay.

Protocol for pre- and post-measurement sessions

Testing sessions consisted of a series of sub-maximum warm-up contractions (the same as the training sessions) to prepare participants for the main tasks which were performed at five different knee-joint angles using their dominant leg. Each type of contraction was completed at all five joint angles (in either an ascending or descending order, randomised between both pre- and post-measurement sessions), before moving on to the next type of contraction: MVCs; EVCs; evoked twitch contractions (see below). For each measurement session, participants were in the laboratory for ~ 1 h and 40 min, with ~ 1 h and 15 min from the first to the last contraction.

Maximal voluntary contractions

Following a series of sub-maximum warm-up contractions (same as for the “training” above) at the first measured angle, participants completed two MVCs at each of the five knee-joint angles. Participants were instructed to extend their knee and “push as hard as possible” for ~ 4 s during MVCs with a ≥ 30 s recovery period between each MVC and a minimum of 3 min rest between each angle. Biofeedback of the torque–time curve was displayed on a computer monitor in front of the participant during MVCs and a horizontal cursor was placed at the peak of the torque–time curve following the first MVC to encourage participants to exceed their best score. Intense verbal encouragement was also offered during all MVCs. During off-line analysis, MVT at each angle was identified as the highest instantaneous torque during both MVCs, and the EMG amplitude of each individual EMG

sensor at MVT was measured as the root mean square during a 500 ms time window (250 ms either side of MVT). EMG amplitude during MVT was subsequently normalized to a joint angle-specific maximal *M*-wave peak-to-peak amplitude (M_{MAX} P–P; see below) recorded from the corresponding EMG sensor during maximum twitch contractions, and these normalized values of each sensor were averaged to calculate whole quadriceps EMG at MVT (QEMG_{MVT}).

Explosive voluntary contractions

Participants then performed 6–8 brief EVCs at each knee joint. Prior to each contraction, participants were instructed to start from rest, without producing prior tension or counter-movement, and on a verbal cue, perform the contraction as “fast and hard” as possible for ~1-s, attempting to reach 75%MVT as quickly as possible and then relax. There was a 20-s rest between EVCs at each angle and a minimum of 5-min rest between angles. Baseline torque displayed on a sensitive scale was used to verify that pre-tension or counter-movement did not occur before contraction onset and if either occurred, the contraction was excluded. Torque onsets for EVC and evoked contractions (both twitch and octet) were identified manually by visual identification by a trained investigator using a systematic approach, as previously described (Tillin et al. 2013b). During off-line analysis, for each knee-joint angle and measurement session, the two EVCs with the highest torque at 100 ms and peak torque > 70% MVT were selected for further analysis. Explosive torque was measured at 50, 100, and 150 ms from torque onset (T_{50} , T_{100} and T_{150} , respectively) for each contraction and then a mean is calculated for each angle during each session, before averaging across duplicate measurement sessions pre and post. Explosive torque also was calculated relative to MVT to identify if maximal and explosive strength changed proportionally from pre to post. sEMG amplitude (root mean square) of each individual sensor during EVCs was measured over epochs of 0–50, 0–100 and 0–150 ms from sEMG onset and amplitudes were normalized to M_{MAX} P–P from the corresponding sensor measured during twitch contractions. Subsequently, normalized values of each sensor were averaged for each epoch to calculate (QEMG_{0-50} , QEMG_{0-100} , QEMG_{0-150}). sEMG onset was determined with a systemic manual method as previously described (Tillin et al. 2013b).

Evoked twitch and octet contractions

After the EVCs and a 2-min rest, transcutaneous femoral nerve stimulation commenced and all evoked contractions were completed, whilst the participant was voluntarily passive. An anode (70 × 100 mm carbon rubber electrode; Electro-Medical Supplies, Greenham, UK) was placed and

secured over the greater trochanter and a cathode (10 mm diameter, protruding 20 mm from a 35 × 55 mm plastic base; Electro-Medical Supplies, Greenham, UK) was positioned over the femoral nerve in the femoral triangle, both coated in conductive gel. Electrical stimulation was then delivered with a constant-current variable-voltage stimulator (DS7AH, Digitimer Ltd., Welwyn Garden City, UK). At the first angle to be tested, the cathode was repositioned and a low-level current (40–60 mA) was delivered until an optimum site was identified based on the twitch torque response and then the cathode was secured with transpore tape. At each angle, stimulation intensity was gradually increased until torque and the peak-to-peak amplitude of the *M*-wave plateaued. Thereafter, three further stimuli were delivered with a current of 150% of the plateau level to measure supramaximal M_{MAX} P–P responses. An interval of 10 s was given between each twitch stimulus and a minimum of 2 min between angles. Twitch peak torque (Twitch PT), Twitch torque at 50 ms (Twitch T_{50}), and M_{MAX} P–P were averaged across the three supramaximal evoked contractions.

After all other procedures had been completed, octet contractions were performed during the second pre- and first post-measurement sessions at all joint angles. Octets were first evoked at progressive currents (~15 s apart) until a plateau in the amplitude of peak torque and peak rate of torque development were achieved; this gradual increase in stimulation intensity procedure was only performed at the first angle tested. Then, two discrete pulse trains (≥15 s apart) were delivered with a higher current (≥20% above the plateau current to ensure supra-maximal stimulation) to evoke maximum octet contractions at each angle. Octets were performed in a counterbalanced order (i.e., half of the participants performed the octets in the order most flexed to most extended and the other half in the opposite order). Octet peak torque (Octet PT) and Octet torque at 50 ms (Octet T_{50}) were measured as the mean across the two maximum octet contractions at each angle. The ratio of voluntary T_{50} /octet T_{50} was used as an additional measure of volitional neural efficacy (Hannah et al. 2012; Buckthorpe et al. 2012). A total of three participants (RT, $n=2$ and CON, $n=1$) were unable to tolerate the discomfort associated with octet stimulation and did not perform this measurement.

Statistical analysis

All data were anonymized prior to analysis. Reproducibility of all measurements over the 4-week intervention period was assessed by calculating the within-participant coefficient of variation of pre- and post-measurements [CV_w ; (SD/mean) × 100] for the CON group. Statistical analysis was performed after individual mean values had been averaged across duplicate test sessions at both timepoints (i.e., pre and post).

As a first step, within-group changes were assessed with a two-way repeated measure ANOVA [time (pre vs. post) \times angle (35° vs. 50° vs. 65° vs. 80° vs. 95°)] for all variables and both groups. To thoroughly investigate the interaction effect (time \times angle), and which specific angle presented higher changes after RT than another (i.e., within-group joint-angle specificity evidence), a within-group two-way repeated measure ANOVA [time (2) \times angle (2)] analysis was also performed for pairwise combinations of angles (e.g. 35° vs. 95° etc.) with Bonferroni stepwise correction applied.

Subsequently, more rigorous analysis of between-group changes was only assessed if within-group analyses revealed a time or a time \times angle effect within one of the groups. In that case, a two-way repeated measures ANOVA [group (2) vs. angle (5)] was performed with absolute change data (post–pre) to identify a main effect of group and group \times angle interaction. If a group \times angle interaction was found, a subsequent two-way repeated measure ANOVA [group (2) \times angle (2)] was also performed for pairwise combinations of angles (i.e., between-group joint-angle specificity evidence). Effect size (ES) was calculated as previously detailed (Cohen 1988) for within- and between-group comparisons, and classified as follows: < 0.20 = “trivial”; 0.20 – 0.49 = “small”; 0.50 – 0.79 = “moderate”; or > 0.80 = “large”. Statistical analysis was performed using SPSS version 23 (IBM Corporation, Armonk, New York, USA), the significance level was set at $P < 0.05$, and all data are reported as means \pm SE unless otherwise stated.

Results

Group characteristics at baseline and joint-angle kinematics

The two groups had similar age, body mass, and height ($P \leq 0.752$). When participant data were collapsed across angles at baseline, no differences ($P \geq 0.271$) were identified between groups (CON vs. RT) for MVT, explosive strength (T_{50} , T_{100} or T_{150}), evoked twitch torque, evoked octet torque, M_{MAX} P–P amplitude, QEMG_{MVT} and QEMG during EVC (absolute or normalized). Based on sagittal plane video recorded during the familiarisation session, the actual knee-joint angles during the plateau phase of MVCs at the five different positions were $33^\circ \pm 2^\circ$, $50^\circ \pm 1^\circ$, $62^\circ \pm 2^\circ$, $78^\circ \pm 2^\circ$, $91^\circ \pm 2^\circ$ at the five positions (mean \pm SD), with changes from rest of $\leq 4^\circ$ at all positions. Nonetheless, we maintained the intended/prescribed joint-angle positions as the terms for the five different positions, i.e., 35°, 50°, 65°, 80°, 95°, throughout the experiment.

Reproducibility of torque and sEMG measurements

Reproducibility data were collapsed across all five angles. The within-participant reliability (CV_W) of the strength measurements was as follows: MVT, 3.9%; T_{150} , 7.8%; T_{100} , 9.6%; and T_{50} , 24.4%. Normalized sEMG measurements presented a CV_W of: QEMG_{MVT} 9.8%; QEMG_{0–150} 14.1%, QEMG_{0–100} 16.1% and QEMG_{0–50} 19.8%. Finally, evoked contractions presented CV_W values of 4.5% for Octet T_{50} , 5.4% Octet PT, 5.0% for Twitch T_{50} , 8.1% Twitch PT and 13.2% for M_{MAX} P–P.

Voluntary torque

Maximum voluntary torque

For RT, within-group comparisons showed a main effect of time (time \times angle ANOVA, $P < 0.001$) and post hoc testing detected increases in MVT at the training angle (65°, $+12 \pm 2\%$), as well as at both of the adjacent angles (80°, $+7 \pm 2\%$; 50°, $+11 \pm 2\%$) and the most extended angle (35°, $+5 \pm 2\%$) after the intervention (All, Bonferroni pre vs. post $P \leq 0.015$; ES ≥ 0.98 “large” for 50° and 65°; ES ≤ 0.37 “small” for 35° and 80°; Fig. 2a). After RT, there was a time \times angle interaction (time \times angle ANOVA, $P < 0.001$) providing evidence of within-group joint-angle specificity, with larger increases at the training angle and the two most adjacent angles compared to at least one other angle (50° $>$ 35° and 80°, $P \leq 0.004$; ES ≥ 1.26 “large”; 65° $>$ 35°, 80° and 95°, $P \leq 0.025$; ES ≥ 1.47 “large”; and 80° $>$ 95°, $P = 0.009$; ES = 0.79 “moderate”). For CON, there were no within-group time or interaction effects (time \times angle ANOVA, $P = 0.406$; Fig. 2b).

Between-group comparisons for MVT change data (i.e., pre to post differences) showed a main effect of group (group \times angle ANOVA, $P = 0.011$; i.e., overall training effect RT $>$ CON). There was also a group \times angle interaction (group \times angle ANOVA, $P = 0.029$), indicating larger improvements after RT vs. CON that were dependent upon angle. Follow-up pairwise group \times angle interactions revealed greater changes for RT than CON between 65° (training angle) vs. 95° ($P = 0.010$; ES = 0.91 “large”), and between 50° vs. 95° ($P = 0.007$; ES = 0.61 “moderate”). Thus, providing the highest level of evidence for angle specificity [i.e., between-group effects (vs. control) that differ according to angle] (Fig. 3).

Explosive voluntary torque

Within-group comparisons from pre to post for both RT and CON did not show a main effect of time or time \times angle interaction effect for T_{50} or T_{100} (time \times angle ANOVA, $P \geq 0.123$; Fig. 4). For T_{150} , there was an increase (main

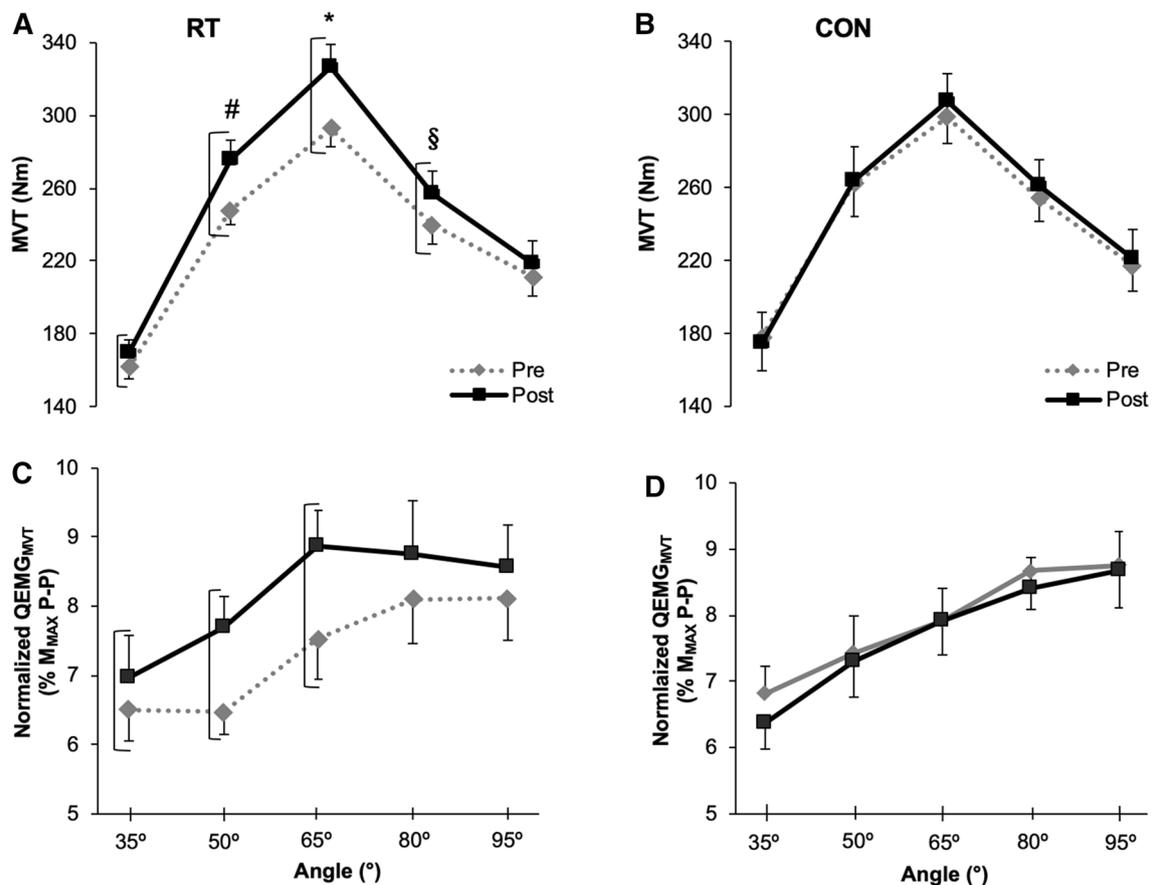


Fig. 2 Knee extensor MVT-angle relationships and normalized QEMG-angle relationships, at knee-joint angles of 35°, 50°, 65°, 80° and 95°. Pre- and post-resistance training (RT; **a, c**) and control (CON; **b, d**) interventions. Brackets indicate within-group effects of time (pre vs. post, post hoc Bonferroni; $P < 0.05$) for both MVT and normalized $QEMG_{MVT}$ after RT. Symbols indicate

within-group angle \times time interactions; specific angles with larger increases after RT than other angles: *increases $>$ than 35°, 80° and 95°; #increases $>$ than 35° and 95°; §increases $>$ than 95° (post hoc pairwise two-way ANOVA of angle \times time, $P < 0.05$). Data are means \pm SE (RT, $n = 13$; CON, $n = 9$)

effect of time) after RT, but not for CON (time \times group ANOVAs: RT $P = 0.029$; CON $P = 0.875$; Fig. 4a, b). Post hoc analysis of the RT group showed that T_{150} increased only at the training angle (65°) after RT (Bonferroni $P = 0.019$; ES = 0.38 “small”; Fig. 4a). Between-group comparisons revealed no group or angle \times group interaction effects for the pre-to-post changes in T_{150} (group \times angle ANOVA, $P \geq 0.227$).

Neuromuscular activation and M_{MAX} amplitude

Within-group comparisons of normalized $QEMG_{MVT}$ (% M_{MAX} P–P) showed a main effect of time after RT (time \times angle ANOVA, $P = 0.004$), but this was not the case for CON (time \times angle ANOVA, $P = 0.382$), and no time \times angle interaction was found for either group (time \times angle ANOVA, both $P \geq 0.502$). For

RT, subsequent post hoc testing revealed normalized $QEMG_{MVT}$ increased at 35° (+ 8 \pm 3%), 50° (+ 19 \pm 5%) and 65° (+ 18 \pm 5%; Bonferroni $P \leq 0.031$; ES = 0.27 “small” for 35° or ES ≥ 0.54 “moderate” for 50° and 65°; Fig. 2d), but not 80° or 95°. Between-group comparisons revealed a main effect of group (group \times angle ANOVA, $P = 0.006$, i.e., greater increases in activation after RT than CON), but not an angle \times group interaction effect for normalized $QEMG_{MVT}$ (group \times angle ANOVA, $P = 0.587$).

Within-group comparisons for normalized QEMG during EVCs ($QEMG_{0-50}$, $QEMG_{0-100}$, $QEMG_{0-150}$) did not show time or time \times angle effects in either RT or CON group (time \times angle ANOVA, $P \geq 0.233$). Within-group measures of M_{MAX} P–P amplitude did not show a main effect for time or an interaction effect for either RT or CON (time \times group ANOVA, $P \geq 0.681$).

Fig. 3 Absolute change (Δ) in MVT (**a**) and normalized QEMG_{MVT} (**b**) at knee-joint angles of 35°, 50°, 65°, 80° and 95° between pre and post for resistance training (RT) and control (CON) groups after a 4-week intervention period. Between-group ANOVA interaction effects (angle \times group) were found for Δ MVT as denoted by the following symbols: *larger difference for RT vs CON for 65° vs 95°; §larger difference for RT vs CON for 50° vs 95°. Data are means \pm SE (RT, $n = 13$; CON, $n = 9$)

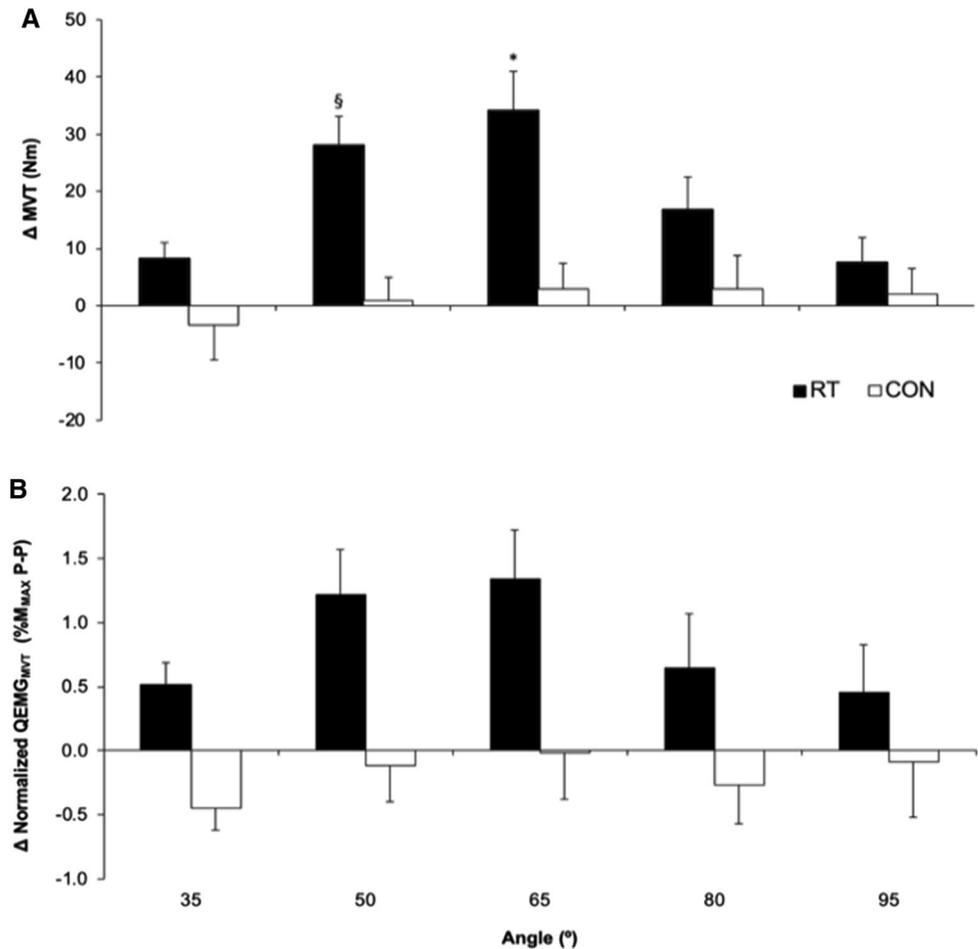
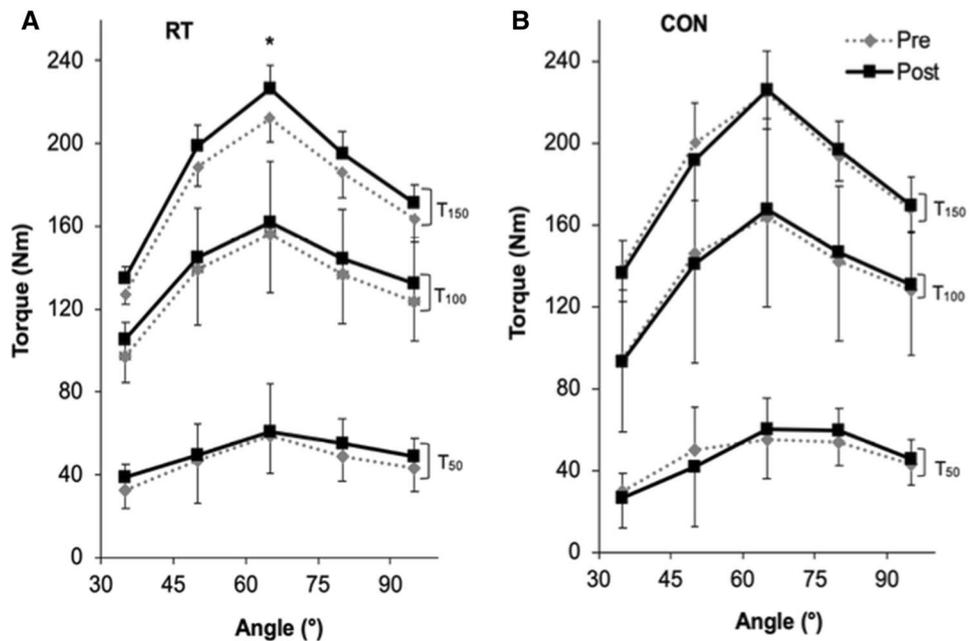


Fig. 4 Knee extensor explosive torque–angle relationships at knee-joint angles of 35°, 50°, 65°, 80° and 95° and measured at three timepoints 50 ms (T_{50}), 100 ms (T_{100}) and 150 ms (T_{150}) from torque onset for resistance training (RT; **a**) and control (CON; **b**) groups pre and post a 4-week intervention period. Differences between group pre- and post-intervention was only detected for RT at 150 ms (pre vs post, post hoc Bonferoni, $P = 0.029$). Symbol * indicates post- higher than pre-training ($P = 0.019$). Data are means \pm SD (RT, $n = 13$; CON, $n = 9$)



Intrinsic contractile properties

Absolute torque

Within-group comparisons for both the RT and CON groups revealed no main effect of time or time \times angle interactions for evoked measures (Twitch T_{50} , Twitch PT, Octet T_{50} ; time \times angle ANOVA, $P \geq 0.142$). However, the RT group, but not CON, presented a main effect of time for Octet PT (time \times angle ANOVA, $P = 0.014$ and 0.245 , respectively). Post hoc testing revealed Octet PT increased after RT at 65° and 50° (Bonferroni pre vs. post $P \leq 0.037$; $ES \leq 0.026$ “small”). Between-group comparisons of Octet PT change data showed no main effect time or group \times angle interaction effect (group \times angle ANOVA, $P \geq 0.440$).

Discussion

The primary aim of this investigation was to determine if joint angle-specific changes in strength were a genuine systematic effect, and whether changes in neuromuscular activation might explain any angle-specific strength changes. RT performed at a mid-range knee-joint angle (65° the angle of peak torque) demonstrated increases in maximal strength at four out of five angles, and the changes at some angles, specifically the training angle and the adjacent more extended angle (65° and 50°), were larger than other positions, demonstrating within-group evidence of joint-angle specificity. This study also found robust, between-group evidence of joint-angle specificity with larger improvements after RT at some angles (65° and 50°) than others (95°) in comparison to CON. Joint-angle specificity was thus confirmed using rigorous experimental design and analysis. Neuromuscular activation showed within-group increases (effects of time) at the training angle and more extended positions (35° , 50° and 65°) only for RT, whilst these changes were largely coincident with the strength changes (increases at the same angles and within the same group); there was no within- or between-group evidence of joint-angle specificity for neuromuscular activation. Moreover, the addition of ECT to the training session did not improve the early phase of the explosive torque production.

As expected, between-group comparisons revealed significant effects of group and thus RT, on changes in maximum strength and associated neural activation, reinforcing the efficacy of short-term RT for these outcomes. Numerous contemporary studies have also found enhanced quadriceps sEMG as an index of neuromuscular activation, post-RT [e.g. (Tillin et al. 2012; de Ruiter et al. 2012; Balshaw et al. 2016)]. Whilst, the aim of the study was not to investigate the precise neural mechanisms whereby the changes in neuromuscular activation occur, increases in neuromuscular

activation after an RT intervention have largely been attributed to increases in motor unit recruitment/synchronization, decrease in recruitment threshold, increases in the firing frequency/discharge rate and/or decrease in neural inhibition (Sale 1988; Gabriel et al. 2006; Folland and Williams 2007; Del Vecchio et al. 2019).

However, the main focus of the current experiment was the joint-angle specificity of these improvements in strength and neuromuscular activation. Within-group analyses showed that RT improved MVT at the training angle ($\sim 12\%$) and at both adjacent angles and the most extended angles. This indicates that improvements at the training angle transfer to angles $> 15^\circ$ of flexion (longer lengths) and $> 30^\circ$ of extension (shorter lengths) from the training angle. Previous work has also suggested greater transfer of isometric strength gains at the training angle to more extended (shorter) than flexed (longer) positions (Weir et al. 1995; Noorkoiv et al. 2014). Moreover, joint-angle specificity was demonstrated within the RT group, with MVT at the training and adjacent angles increasing compared to at least one other angle, and also by more rigorous between-group comparisons showing larger changes after RT at some angles (65° and 50°) than others (95°) in comparison to CON. Therefore, this study provides rigorous evidence that the joint-angle specificity of isometric RT is a genuine effect.

The present study detected increases in agonist neuromuscular activation at MVT (i.e., normalized $QEMG_{MVT}$) after RT at the training angle and more extended knee positions (7–19%, within-group), that is at three of the four positions where the strength gains also occurred in this group, with no changes in strength or activation after CON. These changes in activation would seem unlikely to have occurred at the same angles and in the same group as for the strength gains by chance, and therefore, provide a ready explanation for the increases in maximum strength at these angles. However, we found no within- or between-group evidence of joint-angle specificity for neuromuscular activation. Previous studies investigating the knee-joint angle specificity of RT have detected similar increases in neuromuscular activation after training (Kubo et al. 2006; Noorkoiv et al. 2014), but also no joint-angle specificity for neuromuscular activation. Neuromuscular activation in this study was assessed with sEMG amplitude normalized to M_{MAX} , which is known to reduce the confounding effects of electrode relocation and subcutaneous tissue thickness (Lanza et al. 2018). Nonetheless, sEMG measurements at MVT clearly showed greater between- and within-participant variability than measurements of MVT and this likely impaired the possibility to detect angle-specific training adaptations in neuromuscular activation.

Our previous work has indicated that neuromuscular activation during both the maximal (plateau) and explosive (rising) phases of isometric contractions is joint angle

dependent (Lanza et al. 2017, 2019), and given the extensive evidence for neural adaptations after RT (Folland and Williams 2007; Balshaw et al. 2016), including from the current study, it seems plausible that these adaptation may be joint angle specific, even if current techniques lack the sensitivity to provide definitive evidence. For instance, it is known that the cortical excitability is influenced by joint angle (Mitsushashi et al. 2007; Chye et al. 2010), presumably via muscle, joint and cutaneous feedback. For example, different knee joint angles are thought to alter the stress placed on the anterior cruciate ligament (ACL) activating reflex pathways (i.e., Ia and Ib interneurons) that provide inhibitory input to the alpha motorneurons and thus influencing neuromuscular activation (Johansson et al. 1991). With isometric RT, it is possible that excitatory and/or inhibitory inputs may be up- or downregulated, respectively, to facilitate increased activation at the training angle.

In the present study, there was a modest increase in explosive strength only during the late phase of contraction (150 ms) after RT, and only at the training angle (~ 7%), i.e., no transfer to other angles. Subsequently, there was no evidence of joint angle-specific adaptations in explosive strength. Whilst there were no changes in neuromuscular activation during explosive torque production after RT, Octet PT did increase by ~ 4.3% at 65° and 50° for the RT group only. This change in evoked peak torque indicates a modest morphological adaptation, most likely hypertrophy, may have occurred even within the 4 weeks of this intervention, similar to previous reports of subtle hypertrophic effects within only a few weeks of RT (Seynnes et al. 2007; Buckthorpe et al. 2012; Maeo et al. 2018). Furthermore, muscle size is known to be a determinant of late phase explosive strength (Erskine et al. 2014; Evangelidis et al. 2017) and thus, could account for the modest increase in explosive T_{150} .

Our previous work found quite marked training specificity effects of sustained vs. explosive contraction RT with greater increases in early phase explosive torque after ECT vs. SCT and greater increases in MVT after SCT vs. ECT (Balshaw et al. 2016). In this study, both types of contractions (ECT and SCT) were combined to see if adaptations in both explosive and maximum strength would occur. However, whilst the combined training elicited increased MVT, as we have previously found for SCT (Tillin and Folland 2014; Balshaw et al. 2016), it did not increase explosive torque at any timepoint during the rising/explosive phase of contraction. Thus, the combined training used in this study resulted in changes in function, maximum and explosive strength, similar to SCT alone (Tillin and Folland 2014; Balshaw et al. 2016), with no improvement in early phase explosive strength during the first 100 ms of contraction. In other words, the unique functional adaptation to ECT, improved early phase explosive strength, may be negated when combined with SCT

within the same training session, perhaps suggesting some interference effect of the combined training. Alternatively, as EVT is known to be less reliable (Buckthorpe et al. 2012), and also more sensitive to fatigue (Buckthorpe et al. 2014), than MVT, it is possible that the large number of assessed contractions across five angles may have obscured any changes in EVT. Therefore, the finding of a possible interference effect of SCT and ECT would benefit from replication in a study where the primary focus is the type and combination of RT contractions.

The present study has limitations and strengths that are worth highlighting. One limitation was that to carefully consider the transfer to adjacent joint angles, the positions assessed in this study were $\pm 30^\circ$ of the training angle and thus only 60°, rather than the whole range of knee joint movement. The volume of measurements in the current study was high with maximum and explosive voluntary contractions performed at each of five angles within each measurement session, and this appears to have reduced the reproducibility of the measurements compared to our previous experiments with strength measurements at just one angle [e.g. (Balshaw et al. 2016)]. However, the current study involved averaging data across duplicate measurements sessions both pre and post the intervention period to further improve reproductibility, and these sessions involved a counterbalanced angle order to reduce the possibility of systematic order effects.

Conclusion

In conclusion, after RT, maximal strength increased at four out of five knee-joint angles and we found novel and unique evidence of joint-angle specificity; larger improvements after RT at some angles than others in comparison to CON. Increases in neuromuscular activation occurred at three of the same joint angles as strength gains for the RT group, but not control, giving some support to the notion of increased activation underpinning angle-specific strength gains. However, importantly, there was no evidence of joint angle-specific changes in activation either from within- or between-group analyses, likely due to the variability in the sEMG adaptatons. Finally, the combination of explosive and sustained contractions during each training session did not result in early phase explosive strength gains during a 4-week training period.

Author contributions MBL, TGB, and JPF contributed to the design and implementation of the research to the analysis of the results and to the writing of the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflicts of interest.

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