

Training-specific functional, neural, and hypertrophic adaptations to explosive- vs. sustained-contraction strength training

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1 **TITLE PAGE**

2 **Title:**

3 TRAINING SPECIFIC FUNCTIONAL, NEURAL AND HYPERTROPHIC
4 ADAPTATIONS TO EXPLOSIVE- VS. SUSTAINED-CONTRACTION STRENGTH
5 TRAINING

6

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17

18 **Abbreviated title for running head:**

19 EXPLOSIVE- VS. SUSTAINED-CONTRACTION STRENGTH TRAINING

20

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24

25 **Key words**

26 Resistance exercise; Neural drive; Rate of torque development; Maximum strength;
27 Contractile properties

28

29

30 **Abstract**

31 Training specificity is considered important for strength training, although the functional and
32 underpinning physiological adaptations to different types of training, including brief
33 explosive contractions, are poorly understood. This study compared the effects of 12-wks of
34 explosive-contraction (ECT, n=13) vs. sustained-contraction (SCT, n=16) strength training vs.
35 control (CON, n=14) on the functional, neural, hypertrophic, and intrinsic contractile
36 characteristics of healthy young men. Training involved 40 isometric knee extension
37 repetitions (x3/wk): contracting as fast and hard as possible for ~1 s (ECT); or gradually
38 increasing to 75% of maximum voluntary torque (MVT) before holding for 3 s (SCT).
39 Torque and EMG during maximum and explosive contractions, torque during evoked octet
40 contractions, and total quadriceps muscle volume (QUADS_{VOL}) were quantified pre and post
41 training. MVT increased more after SCT than ECT (23 vs. 17%; effect size [ES]=0.69), with
42 similar increases in neural drive, but greater QUADS_{VOL} changes after SCT (8.1 vs. 2.6%;
43 ES=0.74). ECT improved explosive torque at all time points (17-34%; $0.54 \leq ES \leq 0.76$) due to
44 increased neural drive (17-28%), whereas only late-phase explosive torque (150 ms, 12%;
45 ES=1.48) and corresponding neural drive (18%) increased after SCT. Changes in evoked
46 torque indicated slowing of the contractile properties of the muscle-tendon unit after both
47 training interventions. These results showed training-specific functional changes that
48 appeared to be due to distinct neural and hypertrophic adaptations. ECT produced a wider
49 range of functional adaptations than SCT, and given the lesser demands of ECT this type of
50 training provides a highly efficient means of increasing function.

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55 **New & Noteworthy**

56 Explosive-contraction strength training (ECT) denoted by brief contractions with high rate of
57 torque development produced a wider range of functional adaptations than sustained-
58 contraction strength training (SCT), with improvements in early- and late-phase explosive
59 strength, as well as maximum strength. In contrast, SCT only improved maximum and late-
60 phase explosive strength. The substantially lower loading duration of ECT (7% of SCT)
61 makes this a less-demanding training modality compared to SCT, which may be
62 preferentially tolerated by musculoskeletal patients.

63

64

65 **Introduction**

66 Maximum and explosive strength are two components of skeletal muscle function that can be
67 critical to the performance of human movement. Maximum strength is the greatest amount of
68 force that can be generated, whereas explosive strength reflects the ability to increase force
69 rapidly from a low or resting level (1, 20, 48). Muscle weakness, including low maximum
70 and explosive strength, contributes to the functional limitations experienced by numerous
71 patient groups (35, 42, 43), including osteoarthritis patients (26). Strength training is widely
72 recommended for improving function of all adults (32, 39) and the increases in explosive
73 and/or maximum strength that occur following training may have profound benefits to
74 mobility, locomotion, and quality of life of older individuals and patients (13, 25, 26, 34, 37,
75 44). Whilst training specificity is widely considered important within the context of strength
76 training (8, 12, 18, 21), the functional adaptations to different types of strength training are
77 not well understood, reducing the efficacy of training guidance and prescription. Furthermore,
78 the similarity or specificity of the underpinning neural and contractile adaptations to different
79 training regimes has received relatively little attention.

80

81 Explosive-contraction strength training (ECT), emphasizing rapid torque development during
82 short contractions, is a relatively non-fatiguing training modality that may be well tolerated
83 by patient groups (i.e. osteoarthritis) who commonly report substantial fatigue (36, 38) and
84 therefore may offer improved adherence within these populations. ECT has been found to
85 produce significant increases in both maximum and explosive strength (48). In contrast,
86 conventional strength training typically has a primary emphasis of training with sustained-
87 contractions (SCT) at high loads leading to pronounced fatigue (31) and may neglect rapid
88 torque development. Our recent 4-week intervention study contrasted ECT and SCT finding
89 distinct training-specific adaptations in functional capabilities and neural drive: maximum
90 strength and corresponding electromyography (EMG) increased more after SCT; and early-
91 phase explosive strength and EMG (≤ 100 ms) during the rising/explosive phase of
92 contraction increased more following ECT (45). This demonstrated that at least in the initial
93 stages of a training programme ECT and SCT produce distinct functional and neural
94 adaptations. However the efficacy of longer-term ECT for functional and neural adaptations
95 remains unknown, and the contrasting influence of these training interventions on the
96 intrinsic contractile properties and hypertrophy (volume) of skeletal muscle has yet to be
97 investigated. A more comprehensive comparison of ECT and SCT may facilitate a greater
98 understanding of the influence of training variables, particularly loading duration (high SCT
99 vs. low ECT) and rate of torque development (RTD, high ECT vs. low SCT), on functional
100 and physiological adaptations.

101

102 The purpose of this study was to investigate the efficacy of 12 weeks of ECT, and compare it
103 to SCT and a control group (CON) by assessing the specificity of the functional changes
104 (maximum and explosive strength), as well as the underpinning adaptations in neural drive,

105 intrinsic contractile properties, and muscle volume after these interventions. We hypothesised
106 that ECT and SCT would elicit distinct and specific functional changes (ECT>SCT for early-
107 phase [≤ 100 ms] explosive strength; SCT>ECT for maximum strength), as a result of distinct
108 neural and contractile adaptations.

109

110 **Materials and Methods**

111 Participants

112 Forty-eight young, healthy, asymptomatic, males who had not completed lower-body strength
113 training for >18 months and were not involved in systematic physical training were recruited
114 and provided written informed consent prior to participation in this study that was approved
115 by the Loughborough University Ethical Advisory Committee. Following familiarization
116 participants were randomly assigned to ECT, SCT, or CON groups that were matched for
117 maximum voluntary torque (MVT) and body mass. A total of five participants withdrew from
118 the study (four due to personal reasons and one was excluded due to non-compliance). Forty-
119 three participants (ECT [n=13]; SCT [n= 16]; CON [n=14]) completed the study. Baseline
120 recreational physical activity was assessed with the International Physical Activity
121 Questionnaire (IPAQ, short format (14)).

122

123 Overview

124 Participants visited the laboratory for a familiarisation session involving voluntary maximum
125 and explosive, as well as evoked twitch contractions to facilitate group allocation. Thereafter,
126 two duplicate laboratory measurement sessions were conducted both pre (sessions 7-10 days
127 apart prior to the first training session) and post (2-3 days after the last training session and 2-

128 3 days later) 12-weeks of unilateral knee extensor strength training. Axial T1-weighted MRI
129 scans of the thigh were also conducted pre (5 days prior to the first training session) and post
130 (2-3 days after the final training session). Training and testing were completed with the same
131 isometric apparatus. Training for the ECT and SCT groups involved unilateral isometric
132 contractions of both legs three times a week for 12-weeks (36 sessions in total), whereas
133 CON participants attended only the measurement sessions and maintained their habitual
134 activity. All participants were instructed to maintain their habitual physical activity and diet
135 throughout the study. Laboratory testing sessions involved recordings of the dominant leg
136 isometric knee-extension torque and surface EMG of the superficial quadriceps muscles
137 during voluntary maximum and explosive contractions, as well as evoked maximum twitch
138 and octet contractions (via electrical stimulation of the femoral nerve). Measurement sessions
139 were at a consistent time of day and started between 12:00-19:00.

140

141 Training

142 After a brief warm-up of sub-maximum contractions of both legs, participants completed four
143 sets of ten unilateral isometric knee-extensor contractions of each leg; with sets alternating
144 between dominant and non-dominant legs until 4 sets per leg had been completed. Each set
145 took 60 s with 2 min between successive sets on the same leg. ECT involved short, explosive
146 contractions with participants instructed to perform each contraction “as fast and hard as
147 possible” up to $\geq 80\%$ MVT for ~ 1 s, and then relax for 5 s between repetitions (Fig. 1 A). A
148 computer monitor displayed RTD (10-ms time epoch) to provide biofeedback of explosive
149 performance, with a cursor indicating the highest peak RTD achieved throughout the session,
150 participants were encouraged to achieve a higher peak RTD with each subsequent contraction.
151 The torque-time curve was also shown: firstly, with a horizontal cursor at 80% MVT (target

152 force) to ensure sufficiently forceful contractions, and secondly, on a sensitive scale
153 highlighting baseline torque in order to observe and correct any pre-tension or
154 countermovement.

155

156 SCT involved sustained contractions at 75%MVT, with 2 s rest between contractions. In
157 order to control the RTD these participants were presented with a target torque trace 2 s
158 before every contraction and instructed to match this target, which increased torque linearly
159 from rest to 75%MVT over 1 s before holding a plateau at 75%MVT for a further 3 s. All
160 training participants (ECT and SCT) performed three maximum voluntary isometric
161 contractions (MVCs, see below) at the start of each training week in order to re-establish
162 MVT and prescribe training torques. Torque data from the first training session of weeks 1, 6
163 and 12 were analysed for all training participants (i.e. ECT and SCT) in order to quantify
164 peak loading magnitude (peak torque, mean of all repetitions), loading rate (peak RTD, 50-
165 ms epoch, mean of all repetitions), and loading duration (defined as time >65%MVT per
166 session).

167

168 Force and EMG recording

169 Measurement and training sessions were completed in a rigid custom-made isometric
170 dynamometer with knee and hip angles of 115° and 126° (180° = full extension), respectively.
171 Adjustable straps were tightly fastened across the pelvis and shoulders to prevent extraneous
172 movement. An ankle strap (35 mm width reinforced canvas webbing) was placed ~15% of
173 tibial length (distance from lateral malleolus to knee joint space), above the medial malleolus,
174 and positioned perpendicular to the tibia and in series with a calibrated S-beam strain gauge
175 (Force Logic, Swallowfield, UK). The analogue force signal from the strain gauge was
176 amplified (x370) and sampled at 2,000 Hz using an external A/D converter (Micro 1401;

177 CED Ltd., Cambridge, UK) and recorded with Spike 2 computer software (CED Ltd.,
178 Cambridge, UK). In offline analysis, force data were low-pass filtered at 500 Hz using a
179 fourth-order zero-lag Butterworth filter (33), gravity corrected by subtracting baseline force,
180 and multiplied by lever length, the distance from the knee joint space to the centre of the
181 ankle strap, to calculate torque values.

182

183 Surface EMG was recorded from the superficial quadriceps muscles (rectus femoris [RF],
184 vastus lateralis [VL], vastus medialis [VM]) using a wireless EMG system (Trigno; Delsys
185 Inc., Boston, MA). Following skin preparation (shaving, abrading, and cleansing with 70%
186 ethanol), Single differential Trigno Standard EMG sensors (Delsys Inc., Boston, MA) each
187 with a fixed 1 cm inter-electrode distance were attached at six separate sites over the
188 superficial quadriceps muscles at set percentages of thigh length above the superior border of
189 the patella (RF 65 and 55%; VL 60 and 55%; VM 35 and 30%) and parallel to the presumed
190 orientation of the underlying fibres. EMG signals were amplified at source (x300; 20- to 450-
191 Hz bandwidth) before further amplification (overall effective gain, x909), and sampled at
192 2,000 Hz via the same A/D converter and computer software as the force signal, to enable
193 data synchronization. In offline analysis, EMG signals were corrected for the 48-ms delay
194 inherent to the Trigno EMG system and band-pass filtered (6-500 Hz) using a fourth-order
195 zero-lag Butterworth filter.

196

197 Pre and post measurement sessions

198 Following a brief warm-up of the dominant leg (3 s contractions at 50% [x3], 75% [x3], and
199 90% [x1] of perceived maximum) measurements were completed in the following order.

200

201 Maximum voluntary contractions

202 Participants performed 3-4 MVCs and were instructed to “push as hard as possible” for 3-5 s
203 and rest for ≥ 30 s between efforts. A torque-time curve with a horizontal cursor indicating the
204 greatest torque obtained within that session was displayed for biofeedback and verbal
205 encouragement was provided during all MVCs. Knee extensor MVT was the greatest
206 instantaneous torque achieved during any MVC or explosive contraction during that
207 measurement session. Root mean square (RMS) EMG for a 500 ms epoch at MVT (250 ms
208 either side) was calculated for each electrode site before averaging across the six sites to
209 provide a whole quadriceps measurement ($QEMG_{MVT}$). In addition, RMS EMG at MVT was
210 normalized to M_{MAX} area (see below) from the corresponding EMG electrode site and then
211 averaged across all quadriceps EMG sites.

212

213 Explosive voluntary contractions

214 Participants completed ten explosive voluntary contractions. They were instructed to perform
215 each contraction “as fast and hard as possible” for ~ 1 s, in order to exceed 80%MVT, and
216 then relax for ≥ 15 s between contractions. Contractions with a change in baseline torque (pre-
217 tension or countermovement) of >0.34 Nm in the 300 ms prior to contraction onset were
218 discarded. The three best contractions (highest torque at 100 ms) were analysed in detail for
219 torque and EMG. Voluntary explosive torque was measured at 50, 100, and 150 ms from
220 contraction onset (T_{50} , T_{100} , and T_{150}), before averaging across the three contractions.
221 Explosive torque was also expressed relative to MVT to assess if explosive and maximum
222 strength changed proportionally.

223

224 RMS EMG of each of the quadriceps sensor sites was measured over three time periods: 0-50,
225 0-100 and 0-150 ms from EMG onset of the first agonist muscle to be activated (see below),
226 before averaging to produce overall quadriceps measurements ($QEMG_{0-50}$, $QEMG_{0-100}$,
227 $QEMG_{0-150}$) for the three best contractions. RMS EMG values from each sensor were also
228 normalized to both EMG_{MVT} and M_{MAX} area for that site before averaging. To decide whether
229 to report absolute RMS EMG or RMS EMG normalized to M_{MAX} the intra-participant
230 reproducibility of EMG_{MVT} for both EMG measures was assessed over the 12-week
231 intervention for CON (see below), and the most reproducible measure used. The ratio of
232 Voluntary T_{50} /Octet T_{50} (see below) was used as an additional measure of volitional neural
233 efficacy during the voluntary explosive contractions.

234

235 During offline analysis, all torque and EMG onsets were identified manually by visual
236 identification by one trained investigator using a systematic approach (46, 49) considered to
237 be more valid than automated methods (49). Briefly, torque and EMG signals were initially
238 viewed on an x axis scale of 300 ms prior to the contraction and y axis scales of 0.68 Nm
239 (torque) or 0.05 mV (EMG) (46, 49) before zooming in to determine the instant of the last
240 peak or trough before the signal deflected away from the envelope of the baseline noise.

241

242 Evoked twitch and octet contractions

243 A constant current variable voltage stimulator (DS7AH; Digitimer Ltd., Welwyn Garden City,
244 UK), cathode probe (1-cm diameter, Electro-Medical Supplies Ltd., Wantage, UK), and
245 anode electrode (7 x 10 cm carbon rubber electrode; Electro-Medical Supplies Ltd., Wantage,
246 UK) were used to electrically stimulate the femoral nerve. The cathode and anode were
247 coated with electrode gel and securely taped to the skin over the femoral nerve in the femoral

248 triangle and over the greater trochanter, respectively. Cathode location was determined by
249 delivering single electrical impulses (square wave-pulses of 0.2 ms duration, ≥ 12 s apart) in
250 order to identify the position that elicited the greatest sub-maximum twitch response. The
251 current intensity was progressively increased until plateaus in peak twitch force and peak-to-
252 peak M-wave amplitude were reached. Then three supra-maximal twitch and M_{MAX}
253 responses were evoked (15 s apart) at a higher current ($\geq 50\%$) to ensure supra-maximal
254 stimulation. The following variables were averaged across the three supra-maximal twitch
255 contractions: peak twitch torque (Twitch Peak T); absolute torque (Twitch T_{50}) and torque
256 expressed relative to Twitch Peak T (Relative Twitch T_{50}) at 50 ms after contraction onset;
257 time from contraction onset to peak twitch torque (Twitch TPT); and the cumulative M_{MAX}
258 area from EMG onset to the point where the signal returned to baseline for each of the six
259 EMG sites.

260

261 During the second pre and first post measurement sessions only, octet contractions (eight
262 impulses at 300 Hz) were evoked at progressive currents (≥ 15 s apart) until a plateau in the
263 amplitudes of peak torque and peak RTD were achieved. Then, three discrete pulse trains
264 (≥ 15 s apart) were delivered with a higher current ($\geq 20\%$ to ensure supra-maximal
265 stimulation) to evoke maximum octet contractions. Peak torque (Octet Peak T), absolute
266 torque (Octet T_{50}) and torque expressed relative to Octet Peak T (Relative Octet T_{50}) at 50 ms
267 after contraction onset, and time from contraction onset to Octet Peak T (Octet TPT) were
268 averaged across the three maximum octet contractions. Due to the discomfort caused by the
269 octet contractions a total of seven participants across the three groups were unable to tolerate
270 this measurement.

271

272

273 Muscle volume

274 A 1.5T MRI scan of the dominant leg was made in the supine position at a knee joint angle of
275 $\sim 163^\circ$ using a receiver 8-channel whole body coil (Signa HDxt, GE). T1-weighted axial
276 slices (5 mm thick, 0 mm gap) were acquired from the anterior superior iliac spine to the knee
277 joint space in two overlapping blocks. Oil filled capsules placed on the lateral side of the
278 participants' thigh allowed alignment of the blocks during analysis. MR images were
279 analyzed by two investigators using Osirix software (version 6.0, Pixmeo, Geneva,
280 Switzerland). Pre and post scans of each participant were analyzed by the same investigator.
281 The quadriceps (RF, VL, VM, and vastus intermedius; VI) muscles were manually outlined
282 in every third image (i.e. every 15 mm) starting from the most proximal image in which the
283 muscle appeared. The volume of each muscle was calculated using cubic spline interpolation
284 (GraphPad Prism 6, GraphPad Software, Inc.). Total quadriceps volume ($QUADS_{VOL}$) was
285 the sum of the individual muscle volumes. Inter- and intra-rater reliability for $QUADS_{VOL}$
286 calculated from the repeated analysis of five MRI scans was 1.2% and 0.4%, respectively.
287 Data from one participant was excluded due to excessive movement artifacts.

288

289 Data analysis and statistics

290 All data was anonymized prior to analysis. Reproducibility of the measurements over the 12-
291 week intervention period was calculated for CON (pre vs. post) as within-participant
292 coefficient of variation (CV_W ; $(SD/mean) \times 100$). MVT and $QEMG_{MVT}$ measurements from
293 the duplicate test sessions were averaged to produce criterion pre and post values for
294 statistical analysis; unless the CV_W for the MVT was $\geq 10\%$ (calculated from duplicate test
295 sessions), in which case the lowest MVT value and corresponding $QEMG_{MVT}$ were discarded.
296 Mean T_{50} , T_{100} , and T_{150} and corresponding QEMG ($QEMG_{0-50}$, $QEMG_{0-100}$, $QEMG_{0-150}$)

297 from the duplicate test sessions were used as criterion pre and post values for statistical
298 analysis; unless the CV_W , (calculated from duplicate test sessions at the given time point) for
299 T_{50} was $\geq 20\%$, in which case a weighted mean for all three explosive torque time points and
300 corresponding QEMG measures were used.

301

302 All statistical analyses were performed using SPSS Version 22.0 (IBM Corp., Armonk, NY).
303 Data are reported as means \pm SD; apart from within figures where data are mean \pm standard
304 error of the mean (SE) for presentation purposes. One-way ANOVAs were conducted on all
305 pre-test variables to assess whether baseline differences existed between groups. Unpaired t-
306 tests were used to assess differences in training variables (loading rate, duration, and
307 magnitude) between ECT and SCT. Within-group changes were evaluated with paired t-tests.
308 Comparison of between-group adaptations to the intervention were assessed with repeated
309 measures analysis of co-variance (ANCOVA; group [ECT vs. SCT vs. CON] x time [pre vs.
310 post]), with corresponding pre training values used as covariates. When group x time
311 interaction effects displayed $P < 0.05$ then post-hoc tests were conducted and included the
312 calculation of effect size (ES) and least significant differences (LSD) of absolute changes
313 (pre to post) between groups (i.e., ECT vs. SCT, ECT vs. CON, and SCT vs. CON). ES for
314 absolute change data was calculated as previously detailed for between-subject study designs
315 [30] and classified as: $< 0.20 =$ “trivial”; $0.20-0.50 =$ “small”; $0.50-0.80 =$ “moderate”;
316 or $> 0.80 =$ “large”). Least significant difference (LSD) post-hoc tests were produced from
317 one-way ANCOVAs and were corrected for multiple comparisons (5). We considered there
318 to be good evidence of between-group differences if both $ES > 0.50$ and LSD post-hoc $P < 0.10$.

319

320

321

322

323 **Results**

324 Group characteristics at baseline

325 At baseline no differences (ANOVA, $P \geq 0.767$) were observed between groups for habitual
326 physical activity (IPAQ: ECT 2047 ± 1081 ; SCT 2135 ± 1230 ; CON 2321 ± 1614 metabolic
327 equivalent min/wk), age (ECT 25 ± 2 ; SCT 25 ± 2 ; CON 25 ± 3 yr), body mass (ECT 70 ± 10 ;
328 SCT 71 ± 9 ; CON 72 ± 7 kg), or height (ECT 1.74 ± 0.07 ; SCT 1.75 ± 0.08 , CON 1.76 ± 0.06
329 m). Similarly, no baseline differences were detected for functional, neural, intrinsic
330 contractile properties, or muscle volume.

331

332 Reproducibility of Torque and EMG measurements

333 The reproducibility of pre and post measures for the CON group over the 12-week period was
334 excellent for MVT, T_{100} , and T_{150} (CV_W 2.9, 4.4 and 4.9% respectively), but poor for T_{50}
335 (CV_W 15.7%). Absolute EMG_{MVT} (9.8%) had better CV_W than EMG_{MVT} normalized to M_{MAX}
336 area (14.7%), and therefore, absolute EMG data are presented. Twitch (Twitch T_{50} , Twitch
337 Peak T, Relative Twitch T_{50} , Twitch TPT) and octet (n=11, Octet T_{50} , Octet Peak T, Relative
338 Octet T_{50} , Octet TPT) variables displayed excellent to good CV_W values (1.8-6.1%).

339

340 Training quantification for ECT vs. SCT

341 Loading duration, quantified as time $>65\%$ MVT per session, was greater for SCT than ECT
342 (unpaired t-test $P < 0.001$; Fig. 1 B). Conversely, ECT involved ~ 6 -fold greater RTD per
343 repetition than SCT (unpaired t-test $P < 0.001$; Fig. 1 C). Peak loading magnitude was also
344 slightly greater for ECT than SCT (81 ± 4 vs. $75 \pm 2\%$ MVT; unpaired t-test $P < 0.001$).

345

346

347

348 Voluntary torque

349 MVT increased after ECT and SCT (both paired t-test $P < 0.001$), but not following CON
350 ($P = 0.739$; Table 1 & 4). The absolute increase in MVT was greater than CON for both ECT
351 and SCT (both $ES \geq 2.06$ “large”, LSD $P < 0.001$), and 38% larger after SCT than ECT
352 ($ES = 0.69$ “moderate”, $P = 0.052$; Fig. 2).

353

354 Explosive torque increased at T_{50} , T_{100} , and T_{150} after ECT (paired t-test $P = 0.047$, $P = 0.008$,
355 and $P < 0.001$, respectively; Table 1 & 4). Whereas, there were no changes in explosive torque
356 after CON (paired t-test $0.420 \leq P \leq 0.847$) and only T_{150} increased following SCT ($P < 0.001$)
357 with no change in T_{50} or T_{100} ($0.140 \leq P \leq 0.939$). Group comparisons revealed that ECT
358 produced greater increases in explosive torque than SCT after 100 ms, but not after 150 ms
359 (T_{100} : $ES = 0.72$ “moderate”, LSD $P = 0.092$; T_{150} : $ES = 0.54$ “moderate”, $P = 0.145$), and larger
360 increases than CON from 100 ms onwards (T_{100} : $ES = 0.98$ “large”, $P = 0.042$; T_{150} : $ES = 1.59$
361 “large”, $P < 0.001$). SCT resulted in greater increases than CON only at T_{150} ($ES = 1.48$ “large”,
362 LSD $P = 0.008$).

363

364 Relative explosive torque (%MVT), at all time points, decreased following SCT (paired t-test
365 $0.004 \leq P \leq 0.032$; Table 1), but remained unchanged after ECT and CON ($0.344 \leq P \leq 0.984$).
366 The decrease in relative explosive torque after SCT was greater than ECT (T_{100} : $ES = 0.88$
367 “large”, LSD $P = 0.015$; and T_{150} : $ES = 0.91$ “large”, $P = 0.006$) and CON (T_{100} : $ES = 1.15$ “large”,
368 $P = 0.016$; and T_{150} : $ES = 0.99$ “large”, $P = 0.022$; Fig. 3). Changes in relative explosive torque
369 did not differ between ECT and CON (T_{100} : $ES = 0.11$ “trivial”, LSD $P = 0.844$; and T_{150} :
370 $ES = 0.12$ “trivial”, $P = 0.547$)

371

372

373 Neural drive

374 QEMG_{MVT} increased, or had a tendency to increase, after SCT (paired t-test $P < 0.001$) and
375 ECT ($P = 0.099$), but not CON ($P = 0.130$; Table 2 and 4). The increase in QEMG_{MVT} was
376 greater than CON for both ECT (ES=0.87 “large”, LSD $P = 0.018$) and SCT (ES=2.30 “large”,
377 $P < 0.001$), but was not different between ECT and SCT (ES=0.36 “small”, $P = 0.370$; Fig. 2).
378 QEMG₀₋₅₀, QEMG₀₋₁₀₀, and QEMG₀₋₁₅₀ increased or had a tendency to increase after ECT
379 (paired t-test $P = 0.089$, $P = 0.048$ and $P = 0.003$, respectively; Table 2). There were no changes
380 in explosive QEMG measurements after CON, and only QEMG₀₋₁₅₀ increased after SCT
381 (paired t-test $P = 0.009$; Table 2). Group comparisons showed ECT to increase explosive
382 neural drive by more than CON at all time points (QEMG₀₋₅₀: ES=0.85 “large”, LSD $P = 0.036$;
383 QEMG₀₋₁₀₀: ES=1.07 “large”, $P = 0.018$; QEMG₀₋₁₅₀: ES=1.57 “large”, $P < 0.001$; Fig. 3), and
384 by more than SCT for QEMG₀₋₁₅₀ (ES=0.58 “moderate”, $P = 0.061$) but not earlier periods
385 (QEMG₀₋₅₀: ES=0.58 “moderate”, $P = 0.101$; or QEMG₀₋₁₀₀: ES=0.46 “small”, $P = 0.254$; Fig.
386 3). SCT increased QEMG₀₋₁₅₀ more than CON (ES=1.20 “large”, LSD $P = 0.021$), but this was
387 not the case for earlier periods ($0.30 \leq ES \leq 0.61$ “small” to “moderate”, $0.154 \leq P \leq 0.463$).

388

389 Relative explosive neural drive (as % QEMG_{MVT}) for all time periods decreased after SCT
390 (paired t-test, $0.001 \leq P \leq 0.004$), but not following ECT or CON ($P \geq 0.395$; Table 2). After
391 SCT the decreases in relative QEMG₀₋₁₀₀ were greater than ECT (ES=0.59 “moderate”, LSD
392 $P = 0.086$) and CON (ES=0.99 “large”, $P = 0.045$), as was QEMG₀₋₁₅₀ vs. ECT (ES=0.62
393 “moderate”, $P = 0.066$). Changes in relative explosive QEMG₀₋₁₀₀ and QEMG₀₋₁₅₀ did not
394 differ between ECT and CON ($0.02 \leq ES \leq 0.29$, LSD $0.623 \leq P \leq 0.697$)

395

396 Voluntary T₅₀/Octet T₅₀ ratio appeared to increase after ECT (n=12; pre 42 ± 20% vs. post 53
397 ± 19%) but did not reach statistical significance for the within group change (paired t-test
398 P=0.122) or group x time interaction effect (ANCOVA, P=0.107). No changes in the
399 Voluntary T₅₀/Octet T₅₀ ratio occurred after SCT (n=14; pre 47 ± 15% vs. post 46 ± 19%;
400 paired t-test P=0.772) or CON (n=11; pre 40 ± 18% vs. post 40 ± 17%; P=0.816).

401

402 Intrinsic contractile properties and muscle size

403 Both training groups increased Octet Peak T (paired t-test ECT P=0.001, SCT P=0.015) and
404 Octet TPT (ECT P=0.017, SCT P<0.001), with no change after CON (0.689≤P≤0.986; Table
405 3). Increases in Octet TPT were greater after SCT than CON (ES=1.35 “large”, LSD
406 P=0.009), but not for other comparisons (P≥0.132, 0.42≤ES≤0.74 “small” to “large”). No
407 changes in Octet T₅₀ occurred after ECT, SCT or CON (paired t-test 0.489≤P≤0.857),
408 although Relative Octet T₅₀ decreased after ECT and SCT (both paired t-test P=0.001), but
409 not CON (P=0.638; Table 3). There was no ANCOVA interaction effect for Octet T₅₀ (Table
410 3), however the decreases in Relative Octet T₅₀ after both ECT (ES=1.36 “large”, LSD
411 P=0.086) and SCT (ES=1.37 “large”, P=0.003) were greater than CON, but these changes
412 were similar after ECT and SCT (ES=0.25 “small”, P=0.209; Fig. 4).

413

414 Twitch Peak T was unchanged in all three groups (paired t-test 0.127≤P≤0.821), although
415 Twitch TPT was longer after both training interventions (0.009≤P≤0.047; Table 3), but not
416 CON (P=0.132). No changes in Twitch T₅₀ occurred after ECT, SCT, or CON (paired t-test
417 0.489≤P≤0.857). Relative Twitch T₅₀ decreased after SCT and ECT (paired t-test 0.008≤P
418 ≤0.032), but not CON (P=0.919; Table 3).

419

420 QUADS_{VOL} increased 8.1% after SCT from 1820 ± 274 to 1967 ± 316 cm³ (n= 15; paired t-
421 test P=0.001), but not following ECT (n=13; 1770 ± 252 to 1816 ± 286 cm³; P=0.247) or
422 CON (n=14; 1891 ± 272 to 1906 ± 261 cm³; P=0.550; Table 4). There was a group x time
423 interaction effect for QUADS_{VOL} (ANCOVA, P=0.018), with the change in QUADS_{VOL} after
424 SCT being greater than that following CON (ES=1.15 “large”, LSD P=0.021) and ~3-fold
425 greater than after ECT (ES=0.74 “moderate”, P=0.074; Fig. 5). Increases in QUADS_{VOL} after
426 ECT were not greater than CON (ES=0.27 “small”, LSD P=0.552).

427

428

429 **Discussion**

430 This study compared the specificity of functional adaptations to 12-weeks of ECT vs. SCT
431 and assessed underpinning neural, contractile, and hypertrophic adaptations contributing to
432 these functional changes. MVT increased after both SCT and ECT, but these changes were
433 greater after SCT (+23 vs. +17%). Increases in EMG_{MVT} were similar following SCT and
434 ECT, whilst greater increases in QUADS_{VOL} (+8.1 vs. +2.6%) suggest muscle size rather than
435 neural drive explained the greater improvement in MVT after SCT than ECT. Improvements
436 in early-phase explosive torque production (≤100 ms) only occurred after ECT (+17-34%),
437 were greater than after SCT (at 100 ms) and appeared to be due to increased early-phase
438 neural drive. ECT and SCT both improved explosive strength at 150 ms (+18% vs. +12%)
439 with corresponding increases in neural drive likely explaining the enhancement in late-phase
440 explosive torque production. Octet Peak T increased after training, but there were no changes
441 in the intrinsic contractile explosive capability (Twitch and Octet T₅₀) as the time-course of
442 the evoked response (Octet and Twitch TPT as well as Relative Octet and Twitch T₅₀)
443 decreased after both SCT and ECT, indicating a likely slowing of the muscle’s contractile
444 properties after both training interventions. Overall, the results support our hypothesis of

445 distinct and specific functional changes (ECT>SCT for early-phase explosive strength;
446 SCT>ECT for maximum strength), and this appeared to be due to distinct neural and
447 hypertrophic, but not intrinsic contractile adaptations.

448

449 Both ECT and SCT increased maximum strength, and by more than CON, but with greater
450 increases after SCT (+23 vs. +17%). Maximum strength has been reported to increase by
451 varying extents following both SCT (+11-36%; (1, 4, 9, 24, 40)) and ECT (+7-25%; (7, 41,
452 48)), yet this study is the first to directly compare the magnitude of maximum strength
453 improvements after prolonged training with these different approaches. Loading duration
454 (also referred to as time under tension) and loading magnitude have been suggested to be
455 important training stimuli for maximum strength adaptation (15). Maximum strength
456 improvements after ECT were ~70% of those after SCT, despite ECT involving only 7% of
457 the loading duration (time >65%MVT) and thus considerably less effort and fatigue. In
458 contrast the loading magnitude of the two interventions in the current study were
459 physiologically, if not statistically, quite similar (ECT 81 vs. SCT 75%). Overall this
460 provides evidence that loading magnitude rather than loading duration accounts for the
461 majority of the maximum strength improvement following the first 12 weeks of SCT and is
462 the primary training stimulus. In this case, brief explosive contractions up to a high loading
463 magnitude appear to be an efficient means of increasing maximum strength without the
464 requirement for sustained muscular contractions. Furthermore, if loading magnitude is the
465 primary stimulus for maximum strength gains then it is possible that even higher loading
466 magnitudes than those employed in the current study (i.e. >95%MVT), which may be
467 achievable during very short contractions, could provide an even greater stimulus for
468 enhancing maximum strength. The importance of loading magnitude for maximal strength
469 gains may have application for optimizing training prescription of athletes and patient

470 populations, in particular for patient groups where more sustained contractions may be
471 problematic due to fatigue.

472

473 Neural drive at MVT increased more after both SCT and ECT than CON. Numerous previous
474 studies have found neural drive at MVT (assessed with EMG) to increase after SCT
475 interventions (24, 47), however the current study is the first to show that short duration
476 explosive contractions can produce increases in neural drive at MVT and this likely explained
477 the efficacy of ECT for increasing MVT. In fact there was no difference between ECT and
478 SCT for this neural adaptation (EMG_{MVT}), indicating that loading magnitude rather than
479 loading duration is the primary stimulus for increasing neural drive at MVT. Previous
480 evidence suggests that increased motor unit firing frequency explains enhanced neural drive
481 at MVT after training (27, 28), and this likely accounts for the improvement of both groups in
482 the current study. In contrast, ECT did not stimulate an increase in muscle volume, and
483 therefore, while ECT appears to be effective at enhancing neural aspects of maximum
484 strength it is relatively ineffective at stimulating hypertrophy. Whereas SCT did induce an
485 increase in muscle volume, that was ~3-fold greater than after ECT (+8.1 vs. +2.6%). Thus
486 hypertrophy was sensitive to loading duration and this adaptation appears to explain the
487 larger improvements in maximum strength for SCT vs. ECT. In this case, for longer-term
488 training goals that are primarily reliant on hypertrophic, rather than neural, adaptations
489 loading duration may become the key training variable. These findings may have relevance
490 for athletic and patient groups where increasing muscle volume is a primary training goal.

491

492 Early-phase (first 100 ms) explosive strength increased more after ECT than SCT. In contrast,
493 later-phase explosive strength (T_{150}) was enhanced after both types of training. The
494 improvements in T_{50} and T_{100} following ECT in the current study are consistent with our

495 previous observation that early-phase explosive strength adaptations were highly specific to
496 4-weeks of ECT vs. SCT (45), and demonstrates this to also be the case with more prolonged
497 (12-wks) training. The loading rate (peak RTD) during the short explosive contractions of
498 ECT was almost 6-fold greater than SCT, and therefore, high loading rates, rather than
499 loading magnitudes (similar for ECT and SCT) or duration (greater for SCT) appears to be
500 critical for enhancing early-phase explosive strength. Previous investigations of ECT have
501 consistently reported improvements in explosive strength (7, 22, 23, 41, 45, 48). In contrast,
502 training regimes similar to SCT in the current study have demonstrated both enhanced (1, 6, 9,
503 13, 29, 44) and unchanged (10, 40, 47) explosive strength. The inconsistent changes in
504 explosive strength in these studies may be partly explained by the variable training
505 instructions provided (e.g. an explosive component (13, 40, 44); no explosive component (6,
506 9, 47); or unclear (1, 29)). In our laboratory, we have consistently found no increase in early-
507 phase explosive strength after 4 (47) and now 12 weeks of isometric SCT, as well as 3 and 12
508 weeks of dynamic SCT with isoinertial lifting and lowering (10, 19). Therefore for early-
509 phase explosive strength gains a specific explosive component to the training, involving
510 contractions starting from a low/resting level and performing the rising phase of contraction
511 at a high rate, appears to be important.

512

513 Neural drive during the early-phase of explosive contractions increased only after ECT
514 (EMG_{0-50} and EMG_{0-100} ; Table 2) and these changes were greater than for CON, but not SCT.
515 The Voluntary $T_{50}/Octet T_{50}$ ratio, which provides an alternate measure of early-phase neural
516 drive, increased from 42 to 53% after ECT, but this was not statistically significant due to the
517 large variability in response between participants. Qualitatively however, the group level
518 Voluntary $T_{50}/Octet T_{50}$ ratio response was notably larger after ECT (+26%) than SCT (-2%)
519 or CON (0%). Later-phase neural drive (EMG_{0-150}) was increased after both types of training

520 (Table 2). Overall, the current study shows neural adaptations during the early-phase of
521 explosive contraction that are specific to ECT, that had previously only been documented for
522 a 4-week training period (45), are still present following a more prolonged intervention.
523 Improvements in early-phase explosive torque production (T_{50} and T_{100}) occurred after ECT
524 without increases in muscle size or early-phase intrinsic contractile capacity for explosive
525 torque production (Octet and Twitch T_{50}), supporting the importance of neural drive
526 adaptations for the enhancement of early-phase explosive strength following training.

527

528 Explosive torque and EMG expressed relative to corresponding maximum force and EMG
529 were unchanged with ECT but decreased with SCT (Tables 1-2 and Fig. 3 B and D);
530 highlighting further the comprehensive adaptations to ECT (i.e. proportional increases in both
531 explosive and maximum torques and corresponding neural drive) but not SCT (i.e. increases
532 in only maximum torque and neural drive). These changes after ECT partly oppose our
533 previous findings of a greater proportion of maximum strength and EMG being expressed
534 during explosive contractions after 4 weeks of ECT (45), that may be explained by the
535 apparent slowing of the contractile properties and/or greater changes in MVT, and neural
536 drive at MVT, after ECT in the current study. Neurologically, increases in instantaneous
537 motor unit discharge rates and the number of motor units able to produce high discharge rates
538 during explosive contractions and a degree of transfer of these adaptations to maximum
539 contractions may explain the increases in explosive (early- and late-phase) and maximum
540 neural drive after ECT (16, 17). In contrast, the low loading rates ($385 \text{ Nm}\cdot\text{s}^{-1}$) but high
541 loading magnitudes ($75\% \text{ MVT}$) with SCT may have only stimulated adaptations in discharge
542 rate during the production of larger torques (i.e. the late-phase of explosive torque production
543 and the plateau phase of contraction) (27, 28).

544

545 Overall, ECT denoted by brief contractions with high RTD produced a wider range of
546 functional adaptations than SCT, with improvements in early- and late-phase explosive
547 strength, as well as maximum strength (Table 4). In contrast, SCT only improved maximum
548 strength and late-phase explosive strength (Table 4). The substantially lower loading duration
549 of ECT (7% of SCT) makes this a less-demanding training modality compared to SCT, which
550 may be preferentially tolerated by musculoskeletal patients and older adults. Future research
551 should investigate: (i) whether ECT may be preferentially tolerated by musculoskeletal
552 patients and older adults, and (ii) also evaluate the efficacy of ECT, and underpinning
553 neuromuscular adaptations, in an isoinertial dynamic training model that is more widely
554 accessible.

555

556 The within-group increase in Octet Peak T following both ECT and SCT demonstrated an
557 increase in the maximum contractile capacity of the muscle-tendon unit, although between-
558 group differences were not detected. In contrast, Twitch Peak T was unresponsive to training
559 even after SCT that induced hypertrophic adaptations. Changes in the time-course of evoked
560 responses (Octet and Twitch TPT as well as Relative Octet and Twitch T_{50}) indicated an
561 overall slowing of the contractile properties of the muscle tendon unit after both types of
562 training. This apparent slowing of the intrinsic contractile properties is likely due to
563 decreased expression of myosin heavy chain type IIX fibres after training (2, 3, 11). For SCT,
564 the slower contractile properties may explain why during the early-phase of explosive
565 voluntary contraction relative torque decreased and absolute torque remained unchanged,
566 despite increases in maximum strength. After ECT the slower contractile properties may
567 explain why relative explosive torque remained unchanged despite improved neural drive,
568 and why the increases in absolute explosive torque were more modest than might have been
569 expected based on our previous 4-week training study (45) when presumably any potentially

570 negative morphological changes would have been more limited. Furthermore, even after the
571 brief explosive contractions of ECT the intrinsic contractile properties of the muscle were
572 slowed, which might suggest that these changes may be unavoidable with strength training of
573 previously untrained individuals.

574

575 In conclusion, functional, neural, and hypertrophic adaptations showed marked training
576 specificity. ECT produced wide ranging functional adaptations with increases in early- and
577 late-phase explosive and maximum strength due to neural adaptations, and the very low
578 loading duration of ECT (7% of SCT) makes this a substantially less demanding training
579 modality that may be preferentially tolerated by musculoskeletal patients and older adults.
580 SCT produced a greater improvement in maximum strength, but no improvements in early-
581 phase explosive strength. The similar changes in neural drive at MVT after ECT and SCT
582 (despite a lesser gain in MVT following ECT) indicate that this adaptation is largely
583 dependent on loading magnitude. In contrast the ~3-fold greater hypertrophy after SCT than
584 ECT indicates that this adaptation is dependent on loading duration. Improvements in early-
585 phase explosive torque production (≤ 100 ms) appear to rely on a high RTD to induce specific
586 neural adaptations. Finally, an apparent slowing of the intrinsic contractile properties of the
587 muscle-tendon unit after both types of training likely compromises improvements in
588 explosive strength.

589

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598

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- 738

Figure captions

Fig. 1. (A) Example torque–time curves recorded during three isometric knee extension contractions for two participants performing either explosive-contraction strength training (ECT; black line) or sustained-contraction strength training (SCT; grey line); (B) Loading duration per training session measured by time >65 maximum voluntary torque (MVT) for ECT vs. SCT; and (C) Peak rate of torque development (RTD, 50 ms epoch) during training contractions for ECT vs. SCT. Symbols indicate differences between training groups as determined from unpaired t-tests and are denoted by: †Greater than ECT, §Greater than SCT. Data are mean \pm SE.

Fig. 2. Changes in maximum voluntary torque (MVT) and quadriceps EMG RMS amplitude at MVT ($QEMG_{MVT}$) during isometric knee extensions after explosive-contraction strength training (ECT), sustained-contraction strength training (SCT), and control (CON) interventions. Symbols indicate differences in the magnitude of pre to post changes where post-hoc tests displayed both effect size >0.50 and least significant difference $P < 0.10$: *Greater than CON, †Greater than ECT. Data are mean \pm SE.

Fig. 3 Changes in (A) torque, (B) relative torque (%MVT), (C) quadriceps EMG RMS amplitude, and (D) relative explosive quadriceps EMG RMS amplitude ($\%QEMG_{MVT}$) during explosive isometric knee extensions after explosive-contraction strength training (ECT), sustained-contraction strength training (SCT), and control (CON) interventions. Symbols indicate differences in the magnitude of pre to post changes where post-hoc tests displayed both effect size >0.50 and least significant difference $P < 0.10$: *Different to CON, †Different to ECT, §Different to SCT. Data are mean \pm SE.

Fig. 4. Pre to post changes in Relative Octet T_{50} (the ratio between octet torque 50 ms after contraction onset and octet peak torque) after explosive-contraction strength training (ECT, $n=12$), sustained-contraction strength training (SCT, $n=14$), and control (CON, $n=11$) interventions. Symbols indicate differences in the magnitude of pre to post changes where post-hoc tests displayed both effect size >0.50 and least significant difference $P < 0.10$: *Different to CON. Data are mean \pm SE.

Fig. 5. Pre to post changes in total quadriceps muscle volume ($QUADS_{VOL}$) after explosive-contraction strength training (ECT, $n=13$), sustained-contraction strength training (SCT, $n=15$), and control (CON, $n=14$) interventions. Symbols indicate differences in the magnitude of pre to post changes where post-hoc tests displayed both effect size >0.50 and least significant difference $P < 0.10$: *Greater than CON, †Greater than ECT. Data are mean \pm SE.

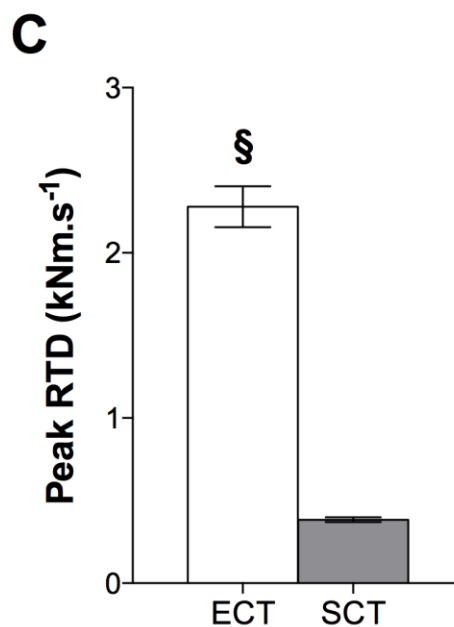
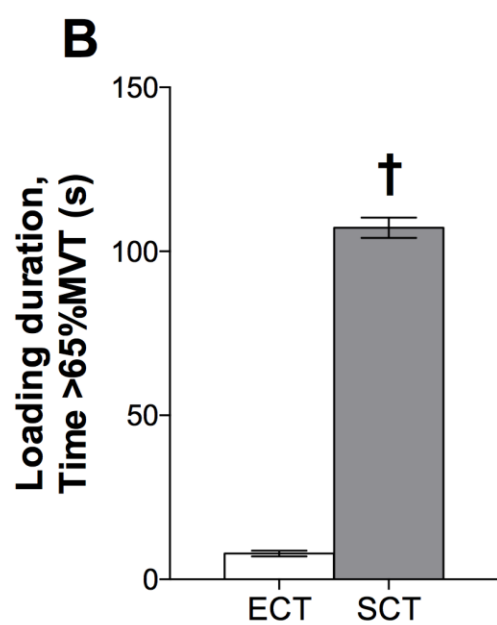
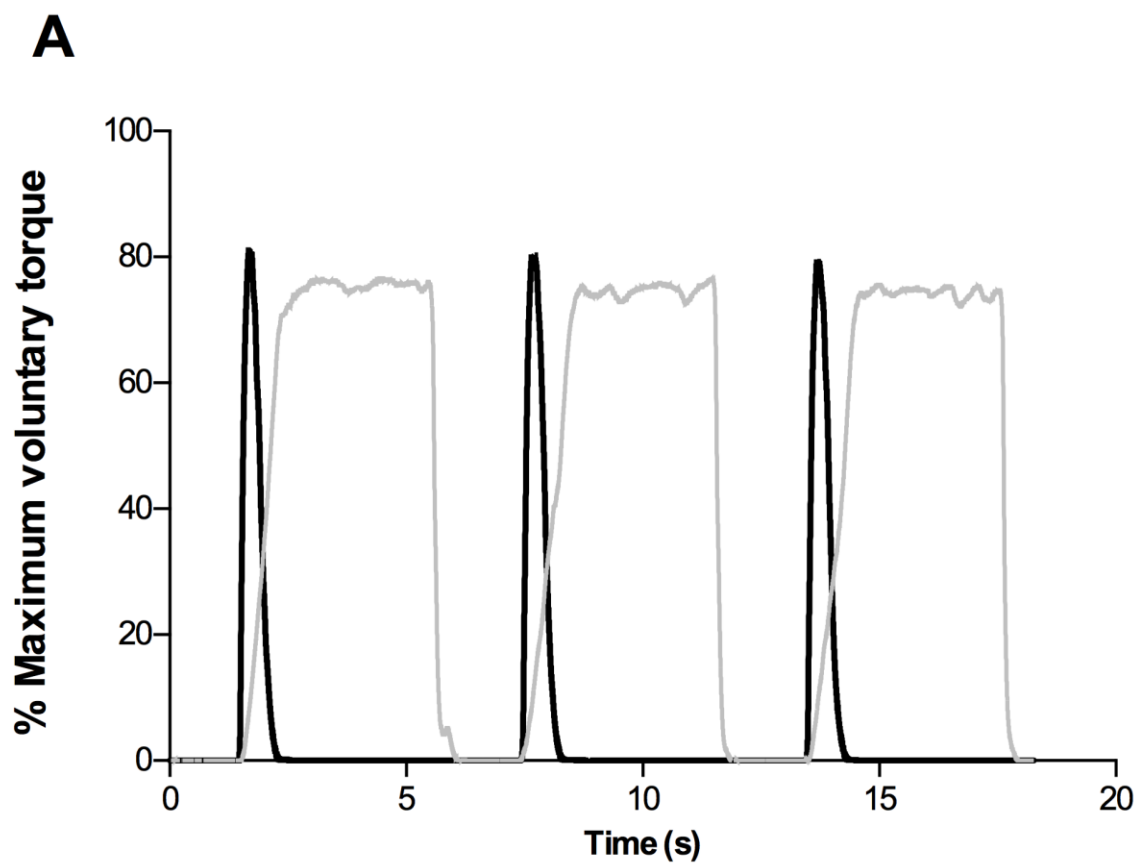


Fig. 1.

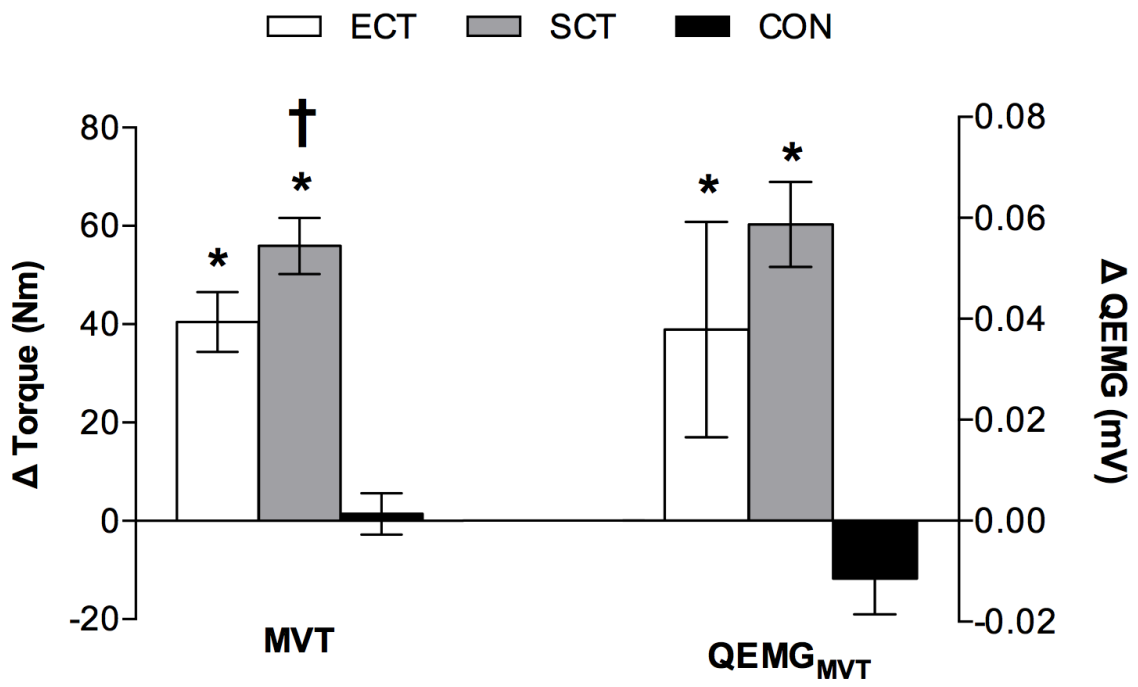


Fig. 2.

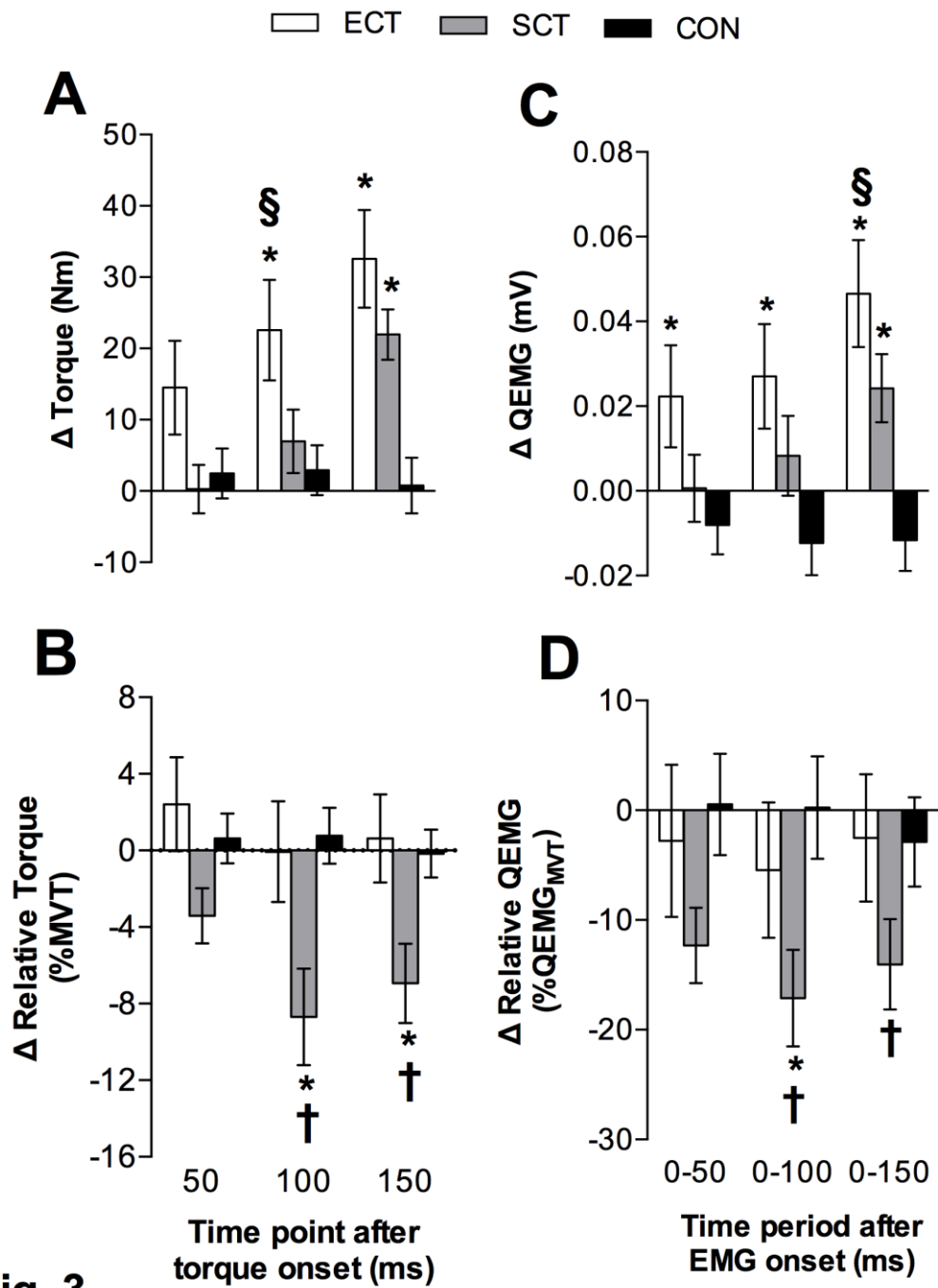


Fig. 3.

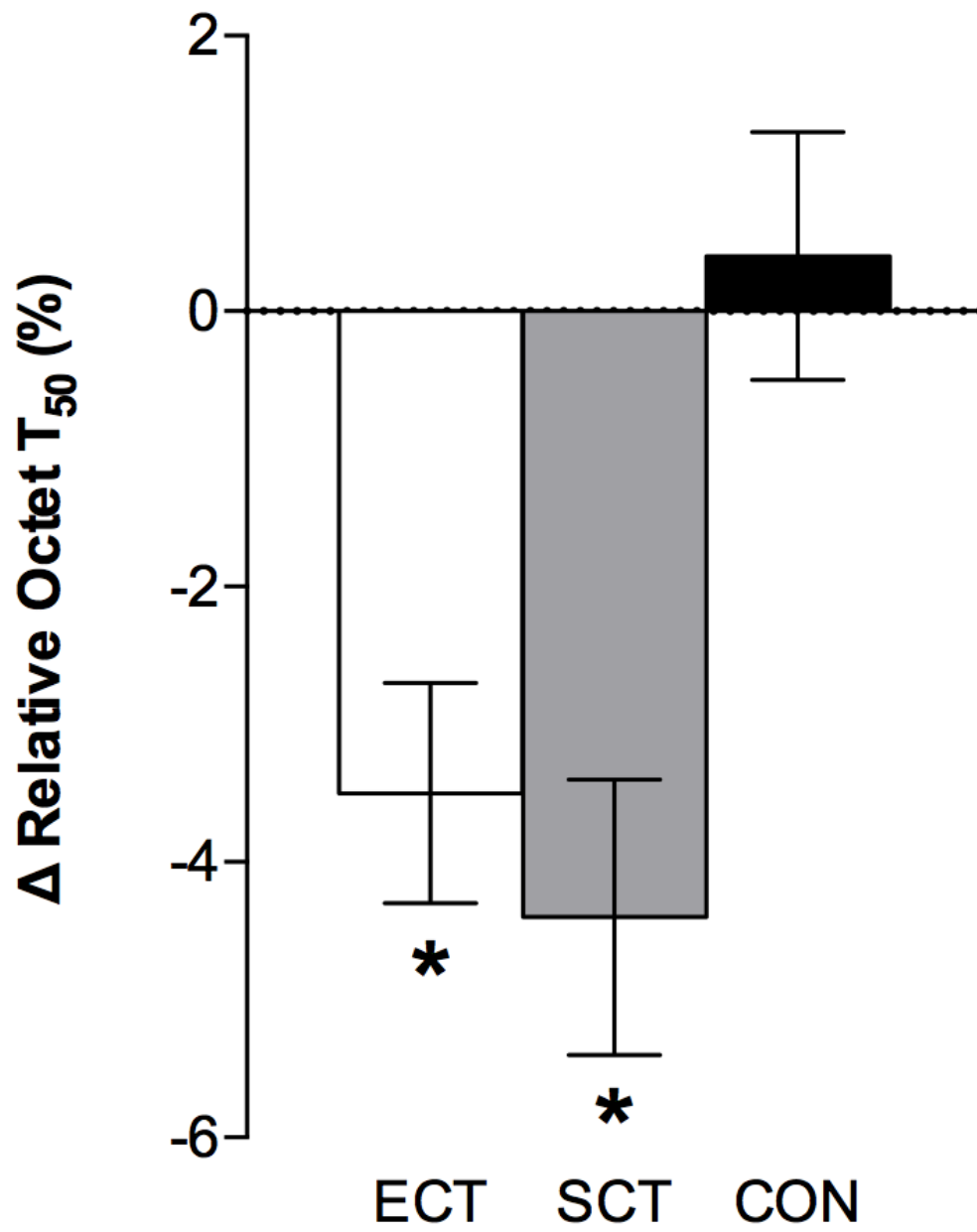


Fig. 4.

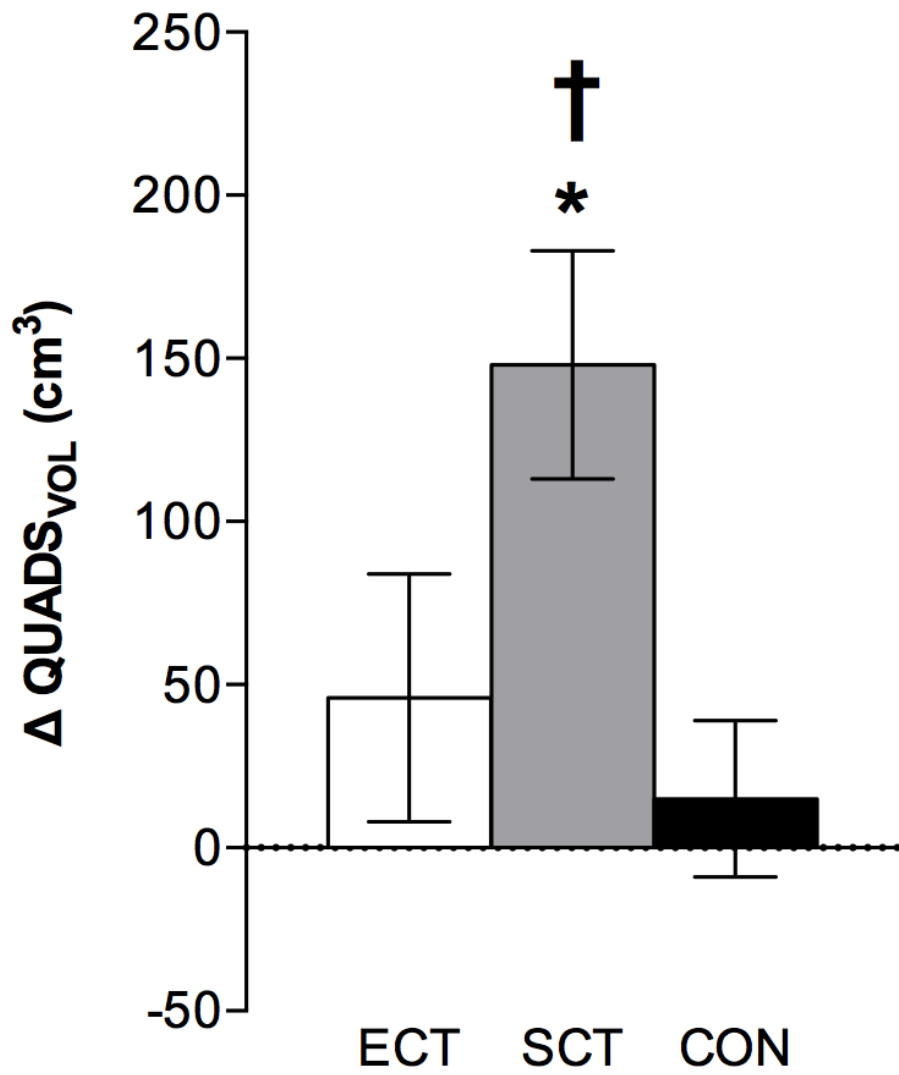


Fig. 5.

Table 1. Maximum voluntary torque (MVT) and explosive torque production (absolute and relative to MVT) pre and post explosive-contraction strength training (ECT, n=13), sustained-contraction strength training (SCT, n=16), and control (CON, n=14) interventions. Explosive torque production is also expressed relative to MVT.

	ECT		SCT		CON		ANCOVA interaction (P value)
	Pre	Post	Pre	Post	Pre	Post	
Absolute (Nm):							
MVT	232 ± 27	272 ± 37***	239 ± 48	295 ± 46***	257 ± 49	259 ± 57	<0.001
T ₅₀	43 ± 20	57 ± 23*	47 ± 21	47 ± 19	39 ± 19	42 ± 19	0.058
T ₁₀₀	132 ± 25	155 ± 29**	138 ± 28	145 ± 22	138 ± 26	141 ± 27	0.036
T ₁₅₀	177 ± 27	210 ± 35***	182 ± 34	204 ± 25***	192 ± 31	193 ± 35	<0.001
Relative (%MVT):							
T ₅₀	18 ± 8	21 ± 7	20 ± 8	16 ± 7*	16 ± 7	16 ± 6	0.055
T ₁₀₀	57 ± 8	57 ± 7	59 ± 10	50 ± 7**	55 ± 9	55 ± 9	0.007
T ₁₅₀	76 ± 6	77 ± 6	77 ± 9	70 ± 7**	75 ± 8	75 ± 7	0.004

Data are mean ± SD. Within-group effects of training were determined from paired t-tests and are denoted by: * (P<0.05), ** (P<0.01), or *** (P<0.001). ANCOVA interaction effects of time (pre vs. post) x group (ECT vs. SCT vs. CON) are reported. Post-hoc comparisons of between group changes are shown in Fig. 2 and 3. ECT, explosive-contraction strength training (n =13); SCT, sustained-contraction strength training (n= 16); CON, control; T, explosive torque (at 50 ms intervals from torque onset).

Table 2. EMG recorded at maximum voluntary torque (EMG_{MVT}) and during explosive contractions (absolute and relative to EMG_{MVT}) pre and post explosive-contraction strength training, sustained-contraction strength training, and control interventions.

	ECT		SCT		CON		ANCOVA interaction (P value)
	Pre	Post	Pre	Post	Pre	Post	
Absolute (mV):							
EMG_{MVT}	0.21 ± 0.08	$0.25 \pm 0.10\ddagger$	0.18 ± 0.07	$0.23 \pm 0.08^{***}$	0.19 ± 0.07	0.17 ± 0.06	0.001
EMG_{0-50}	0.10 ± 0.06	$0.12 \pm 0.07\ddagger$	0.08 ± 0.05	0.08 ± 0.05	0.08 ± 0.05	0.07 ± 0.04	0.033
EMG_{0-100}	0.16 ± 0.07	$0.18 \pm 0.08^*$	0.13 ± 0.05	0.13 ± 0.06	0.13 ± 0.06	0.12 ± 0.05	0.022
EMG_{0-150}	0.16 ± 0.07	$0.21 \pm 0.08^{**}$	0.14 ± 0.05	$0.16 \pm 0.06^{**}$	0.15 ± 0.06	0.14 ± 0.05	<0.001
Relative (%EMG_{MVT}):							
EMG_{0-50}	49.2 ± 22.8	46.5 ± 16.6	46.6 ± 21.2	$34.3 \pm 14.4^{**}$	41.2 ± 17.2	41.8 ± 20.6	0.102
EMG_{0-100}	78.2 ± 17.6	72.7 ± 16.1	75.3 ± 23.2	$58.1 \pm 17.3^{**}$	71.8 ± 16.1	72.0 ± 23.6	0.031
EMG_{0-150}	83.6 ± 15.9	81.1 ± 13.0	81.2 ± 19.9	$67.2 \pm 15.9^{**}$	79.5 ± 15.1	76.7 ± 18.2	0.048

Data are mean \pm SD. Within-group effects of training were determined from paired t-tests and are denoted by: * ($P < 0.05$), ** ($P < 0.01$), *** ($P < 0.001$), or \ddagger ($P \leq 0.10$). ANCOVA time (pre vs. post) \times group (ECT vs. SCT vs. CON) interaction effects are also reported. Post-hoc comparisons of between group changes are shown in Fig. 2 and 3. ECT, explosive-contraction strength training ($n = 13$); SCT, sustained-contraction strength training ($n = 16$); CON, control; EMG_{0-50} , EMG_{0-100} , EMG_{0-150} , explosive contractions over three time periods from EMG onset (0-50, 0-100, 0-150 ms).

Table 3. Intrinsic contractile properties assessed by evoked torque production during octet and twitch contractions pre and post explosive-contraction strength training, sustained-contraction strength training, and control interventions.

	ECT		SCT		CON		ANCOVA interaction (P value)
	Pre	Post	Pre	Post	Pre	Post	
Octet:							
Octet T ₅₀ (Nm)	101 ± 12	105 ± 15	107 ± 14	106 ± 13	108 ± 14	109 ± 16	0.365
Octet Peak T (Nm)	159 ± 20	174 ± 23**	171 ± 23	183 ± 24*	177 ± 26	177 ± 26	0.077
Relative Octet T ₅₀ (%)	64 ± 5	60 ± 4**	63 ± 3	58 ± 3**	61 ± 2	61 ± 3	0.006
Octet TPT (ms)	121 ± 7	127 ± 7*	121 ± 6	130 ± 6***	123 ± 6	124 ± 5	0.010
Twitch:							
Twitch T ₅₀ (Nm)	37 ± 8	38 ± 11	39 ± 9	40 ± 8	43 ± 12	43 ± 10	0.865
Twitch Peak T (Nm)	43 ± 9	45 ± 12	47 ± 11	50 ± 10	52 ± 14	52 ± 12	0.535
Relative Twitch T ₅₀ (%)	86 ± 6	83 ± 6*	83 ± 5	81 ± 4**	82 ± 5	82 ± 3	0.157
Twitch TPT (ms)	73 ± 8	76 ± 7*	73 ± 5	77 ± 4**	78 ± 4	76 ± 3	0.101

Data are mean ± SD. Within-group effects of training were determined from paired t tests and are denoted by: * (P < 0.05), ** (P < 0.01), or *** (P < 0.001). ANCOVA interaction effects of time (pre vs. post) x group (ECT vs. SCT vs. CON) are reported. Relative octet and twitch measures are expressed as percentage of peak torque during these contractions. Participant numbers for: octet variables, ECT, n=12; SCT, n=14; CON, n=11; twitch variables, ECT, n=13; SCT, n=16; CON, n=14. ECT, explosive-contraction strength training; SCT, sustained-contraction strength training; CON, control.

Table 4. Summary of within-group changes from pre to post training in functional, neural, hypertrophic, and intrinsic contractile properties after explosive-contraction strength training (ECT), sustained-contraction strength training (SCT), and control (CON) interventions. The direction of the changes are shown by ↑ or ↓ with the percentage change in the group mean also shown. Non-significant changes are indicated by ↔.

	ECT	SCT	CON
Functional:			
MVT (Nm)	↑+17%	↑+23%	↔
Explosive T ₅₀ (Nm)	↑+34%	↔	↔
Explosive T ₁₀₀ (Nm)	↑+17%	↔	↔
Explosive T ₁₅₀ (Nm)	↑+18%	↑+12%	↔
Neural drive:			
EMG _{MVT} (mV)	↑+18%	↑+33%	↔
EMG ₀₋₅₀ (mV)	↑+23%	↔	↔
EMG ₀₋₁₀₀ (mV)	↑+17%	↔	↔
EMG ₀₋₁₅₀ (mV)	↑+28%	↑+18%	↔
Hypertrophy:			
QUADS _{VOL} (cm ³)	↔	↑+8%	↔
Contractile properties:			
Octet Peak T (Nm)	↑+9%	↑+7%	↔
Octet TPT (ms)	↑+5%	↑+7%	↔
Twitch TPT (ms)	↑+4%	↑+5%	↔