



HAL
open science

Gonad-related factors promote muscle performance gain during postnatal development in male and female mice

Vanessa Ueberschlag-Pitiot, Amalia Stantzou, Julien Messéant, Megane Lemaitre, Daniel Owens, Noirez Philippe, Pauline Roy, Onnik Agbulut, Daniel Metzger, Arnaud Ferry

► To cite this version:

Vanessa Ueberschlag-Pitiot, Amalia Stantzou, Julien Messéant, Megane Lemaitre, Daniel Owens, et al. Gonad-related factors promote muscle performance gain during postnatal development in male and female mice. *AJP - Endocrinology and Metabolism*, 2017, 313 (1), pp.E12-E25. 10.1152/ajpendo.00446.2016 . hal-03677800

HAL Id: hal-03677800

<https://hal.science/hal-03677800v1>

Submitted on 30 Apr 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



LJMU Research Online

Ueberschlag-Pitiot, V, Stantzou, A, Messéant, J, Lemaitre, M, Owens, DJ, Noirez, P, Roy, P, Agbulut, O, Metzger, D and Ferry, A

Gonad-related factors promote muscle performance gain during postnatal development in male and female mice

<http://researchonline.ljmu.ac.uk/id/eprint/7509/>

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Ueberschlag-Pitiot, V, Stantzou, A, Messéant, J, Lemaitre, M, Owens, DJ, Noirez, P, Roy, P, Agbulut, O, Metzger, D and Ferry, A (2017) Gonad-related factors promote muscle performance gain during postnatal development in male and female mice. American Journal of Physiology - Endocrinology And

LJMU has developed **LJMU Research Online** for users to access the research output of the University more effectively. Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Users may download and/or print one copy of any article(s) in LJMU Research Online to facilitate their private study or for non-commercial research. You may not engage in further distribution of the material or use it for any profit-making activities or any commercial gain.

The version presented here may differ from the published version or from the version of the record. Please see the repository URL above for details on accessing the published version and note that access may require a subscription.

For more information please contact researchonline@ljmu.ac.uk

<http://researchonline.ljmu.ac.uk/>

1 **Gonad-related factors promote muscle performance gain during postnatal**
2 **development in male and female mice**

3

4 Vanessa Ueberschlag-Pitiot ¹, Amalia Stantzou², Julien Messéant ², Megane Lemaitre²,
5 Daniel J. Owens², Philippe Noirez ^{3,4}, Pauline Roy², Onnik Agbulut ⁵, Daniel Metzger ¹,
6 Arnaud Ferry ^{2,4}

7

8 1- Institut de Génétique et de Biologie Moléculaire et Cellulaire, Université de Strasbourg,
9 CNRS UMR7104/INSERM U964, Illkirch, France

10 2- Sorbonne Universités, Université Pierre et Marie Curie-Paris6, Myology Research Center,
11 UM76 and INSERM U974 and CNRS FRE 3617 and Institut de Myologie, Paris, France

12 3- Institut de Recherche biomédicale et d'epidemiologie du Sport, EA 7329, Institut National
13 du Sport de l'Expertise et de la Performance, Laboratory of Excellence GR-Ex, Paris,
14 France

15 4-Université Sorbonne Paris Cité, Université Paris Descartes, Paris, France.

16 5- Sorbonne Universités, Université Pierre et Marie Curie-Paris6, Institut de Biologie Paris-
17 Seine, UMR CNRS 8256, Biological Adaptation and Ageing, Paris, France

18

19 Correspondance :

20 A. Ferry

21 G.H. Pitié-Salpêtrière, 47, bld de l'Hôpital, Bâtiment Babinski

22 INSERM U974

23 75651 Paris cedex 13,

24 France.

25 arnaud.ferry@upmc.fr

26 Abstract

27

28 In order to better define the role of male and female gonad-related factors (MGRF,
29 presumably testosterone, and FGRF, presumably estradiol, respectively) on mouse hindlimb
30 skeletal muscle contractile performance/function gain during postnatal development, we
31 analysed the effect of castration initiated before puberty in male and female mice. We found
32 that muscle absolute and specific (normalized to muscle weight) maximal forces
33 were decreased in 6-month old male and female castrated mice, as compared to age- and
34 sex-matched intact mice, without alteration in neuromuscular transmission. Moreover,
35 castration decreased absolute and specific maximal powers, another important aspect of
36 muscle performance, in 6-month old males, but not in females. Absolute maximal force was
37 similarly reduced by castration in 3-month old muscle fibre androgen receptor (AR) -
38 deficient and wild-type male mice, indicating that the effect of MGRF was muscle fibre AR
39 independent. Castration reduced the muscle weight gain in 3-month mice of both sexes and
40 in 6-month females but not in males. We also found that bone morphogenetic protein
41 signaling through Smad1/5/9 was not altered by castration in atrophic muscle of 3-month old
42 mice of both sexes. Moreover, castration decreased the sexual dimorphism regarding muscle
43 performance. Together these results demonstrated that in the long-term MGRF and FGRF
44 promote muscle performance gain in mice during postnatal development, independently of
45 muscle growth in males, largely via improving muscle contractile quality (force and power
46 normalized) and that MGRF and FGRF also contribute to sexual dimorphism. However, the
47 mechanisms underlying MGRF and FGRF actions remain to be determined.

48

49 Keywords

50 Skeletal muscle; postnatal development; androgen deficiency; estrogen deficiency; maximal

51 force; maximal power, muscle fibre androgen receptor, muscle contractile quality.

52 Introduction

53

54 The postnatal growth of skeletal muscle is due to muscle fibre hypertrophy (71) resulting
55 from a high protein synthesis rate (19). After 1 month of age, the increase in fibre diameter
56 in mice occurs without addition of myonuclei provided by satellite cells (71). Male gonad-
57 related factors (MGRF), in particular androgens (testosterone), are thought to play an
58 important role in the postnatal development and maintenance of skeletal muscle mass, and
59 sexual dimorphism of skeletal muscle. It is thought that the actions of androgens are mainly
60 exerted through binding to the androgen receptor (AR), which directly modulates the
61 transcription of target genes. In skeletal muscle, AR has been reported in satellite cells,
62 muscle fibres and other cell lineages. Several animal studies reported that androgen
63 deficiency resulting from castration of adult male animals causes variable levels of muscle
64 atrophy (2, 9, 11, 30, 35, 37, 64), supporting the idea that MGRF play a role in the
65 maintenance of muscle size. Less is known about the role of endogenous androgens, whose
66 blood levels increase at puberty, on muscle contractile performance (function) gain during
67 the postnatal development. Since muscle size is an important determinant of muscle
68 performance, i.e. absolute maximal force and power, it is hypothesized that endogenous
69 androgens contribute to the increase in muscle performance after puberty, but the target cells
70 are unknown. Moreover, it remains largely unknown whether endogenous androgens affect
71 specific maximal force and power (absolute maximal force or power/muscle weight) after
72 puberty, i.e muscle contractile quality, another key determinant of muscle performance.

73

74 Several recent studies concluded that female gonad-related factors (FGRF), in particular
75 estrogens (estradiol), positively regulate absolute maximal force in adult female mice (7, 25,
76 40, 41, 49). Three estrogen receptors, ER α , ER β , and the G-protein coupled receptor (Gper),

77 have been identified in skeletal muscles. [SEP] Moreover, it was reported that some beneficial
78 effects of estrogens on muscle contractility can be very rapid (within 30 min) in adult female
79 mice, suggesting a non-genomic mechanism and that estrogens can affect muscle quality
80 (40). However, the roles of FGRF on muscle performance gain during the postnatal
81 development are not well established in female mice. Indeed, it has been reported that
82 during postnatal development, estrogens decrease absolute maximal force (67) or have no
83 effect in female rats (42).

84

85 Despite recent developments, there is a tremendous lack of understanding of sex-based
86 differences in muscle performance. Overall, evidence to date suggests that muscle
87 performance is sex-dependent (15, 23, 27, 32–34, 62). Indeed, several studies reported that
88 absolute maximal force and power are greater in adult male mice as compared to adult
89 female mice (15, 33, 62), whilst others have not found such differences (23, 28). It is
90 postulated that FGRF and MGRF contribute to the sexual dimorphism regarding muscle
91 performance, however this remains to be firmly established.

92

93 In order to further characterize the role of MGRF and FGRF on postnatal development of
94 muscle contractile performance, i.e. absolute isometric maximal force and absolute maximal
95 power derived from force-velocity relationship, we analyzed in adult male and female mice
96 the effects of castration initiated before puberty. Absolute isometric maximal force and
97 power derived from force-velocity relationship are two important aspects of muscle
98 performance during locomotion and muscular exercise, ie. to accomplish work, although
99 they overestimate the force and power output of a muscle during in vivo dynamic muscle
100 contractions (36). Our general hypothesis was that MGRF and FGRF play important roles in
101 performance gain in male and female mice respectively, between the age of 1 month and 6

102 months. We also tested the hypothesis that castration before puberty decreases sexual
103 dimorphism regarding muscle performance in the adult stage. Moreover, we analyzed the
104 effect of castration before puberty in the absence of muscle fibre AR in order to determine
105 whether AR mediates the potential role of MGRF in this cell type. To address this objective,
106 we used male mice with loss of muscle fibre AR ($AR^{skm-/y}$ mice) that were castrated before
107 puberty or not. If it is the case, the effect of castration before puberty should be reduced in
108 the absence of muscle fibre AR as compared with the presence of AR. We also analysed the
109 effect of castration on several key functional, cellular and molecular determinants of muscle
110 contractile performance that include muscle contractile quality, i.e. specific maximal force
111 and power, neuromuscular transmission, fibre atrophy, fibre type composition, fibrosis and
112 remodeling pathways involved in muscle growth and physiology (such as bone
113 morphogenetic protein signaling, ubiquitin ligases, MSTN, IGF-1).

114

115

116 Materials and Methods

117

118 Mice

119

120 All procedures were performed in accordance with European legislations, in conformity
121 with the Public Health Service Policy on Humane Care and Use of Laboratory Animals, and
122 were approved by the Comité d'éthique en expérimentation animale Charles Darwin #5
123 (Ministère de l'Education Nationale, de l'Enseignement Supérieur et de la Recherche,
124 France)(Autorisation de projet # 01361.03). Male and female wild type mice (C57BL/6
125 background) were analyzed at the age of 1 month, 1.5 month, 3 months and 6 months. Body
126 weights are shown in Table 1. Body weights were decreased in 3-month old male castrated
127 mice and increased in 6-month old castrated female, as compared to age-and sex-matched
128 intact mice ($p < 0.05$). Therefore, these results indicate no reduction in muscle demand
129 during standing and locomotion at the age of 6 months. We also used muscle fibre AR
130 deficient male mice (referred to below as $AR^{skm-/y}$)(on a C57BL/6 background). $AR^{skm-/y}$
131 mice were generated by breeding female $AR^{L2/L2}$ mice carrying “floxed” AR L2 alleles with
132 male HSA-Cre transgenic mice, as described previously (9, 18). Sex matched wild-type
133 littermates ($AR^{L2/y}$ mice) were used as controls. Male and female mice were castrated
134 (ablation of gonads) at 1 month of age, before the onset of puberty (57).

135

136 Muscle contractile performance

137

138 Absolute isometric maximal force and power of the tibialis anterior (TA) muscle were
139 evaluated by measuring the *in situ* muscle contractions in response to nerve stimulation, as
140 described previously (22, 62, 69). Some plantaris muscles were also measured (18). Mice

141 were anesthetized using pentobarbital (60 mg/kg intraperitoneally). Body temperature was
142 maintained at 37°C using radiant heat. The knee and foot were fixed with pins and clamps,
143 and the distal tendon of the muscle was attached to a lever arm of a servomotor system
144 (305B, Dual-Mode Lever, Aurora Scientific) using a non-elastic thread. The sciatic nerve
145 was proximally crushed and distally stimulated by a bipolar silver electrode using
146 supramaximal square wave pulses of 0.1 ms duration. Muscle was also directly stimulated
147 after nerve stimulation at the frequency corresponding to maximal force in order to directly
148 initiate muscle contraction in the case of neurotransmission failure (16). Stimulating
149 electrodes were positioned on the midbelly of the muscle and the muscle was stimulated
150 with a high strength voltage (80V). We measured the absolute maximal force that was
151 generated during isometric contractions in response to electrical stimulation (frequency of
152 75–150 Hz, train of stimulation of 500 ms). Absolute maximal force was determined at L0
153 (length at which maximal tension was obtained during the tetanus). Absolute maximal force
154 was normalized to the muscle mass as an estimate of specific maximal force, i.e. muscle
155 contractile quality, a key determinant of muscle performance.

156

157 Force-velocity data were then obtained by eliciting contractions in response to sciatic nerve
158 stimulation (500 ms, 125 Hz) at 6 different afterloads (over a range of approximately 10-
159 50% absolute maximal force). The sciatic nerve was stimulated for 700 ms (125 Hz). A
160 maximal isometric contraction of the muscle was initiated during the first 200 ms. Then, the
161 muscle shortened during the last 300 ms against the load. Each contraction was separated by
162 a 1 min rest period. The shortening velocity was measured during the first 20 ms of the
163 shortening period. Absolute power was calculated (power = afterload x shortening velocity)
164 and absolute maximal power was reported (mW). Specific maximal power (mW/g) was
165 calculated by dividing maximal power by muscle weight, as another index of muscle

166 contractile quality and important determinant of muscle performance. After contractile
167 measurements, the animals were sacrificed by cervical dislocation and muscles were
168 dissected and weighed before being processed for downstream analyses.

169

170 Neuromuscular junction morphology

171

172 Neuromuscular junction (NMJ) analysis was performed on isolated muscle fibres as
173 previously described (47, 59). Briefly, plantaris muscles were dissected and fixed in
174 4%PFA/PBS for 30 min and rinsed with PBS at room temperature. Isolated muscle fibres
175 were washed three times for 15 min in PBS, incubated for 30 min with 100 mM glycine in
176 PBS and rinsed in PBS. Samples were permeabilized and blocked in blocking buffer (3%
177 BSA/5% goat serum/0.5% Triton X-100 in PBS) for 4 hours at room temperature. They
178 were then incubated overnight at 4°C with rabbit polyclonal antibodies against 68 kDa
179 neurofilament (NF, Millipore Bioscience Research Reagents, 1:1000) and synaptophysin
180 (Syn, Zymed, 1:200) in blocking buffer. After four 1-hour washes in PBS, muscles were
181 incubated overnight at 4°C with Cy3-conjugated goat anti-rabbit IgG (Jackson
182 Immunoresearch Laboratories, 1:500) and Alexa Fluor 488-conjugated α -bungarotoxin (α -
183 BTX, Life Technologies, 1:1000) in blocking buffer. After four 1-hour washes in PBS,
184 isolated muscle fibres were then flat-mounted in Vectashield (Vector Laboratories)
185 mounting medium. Confocal images were acquired using Leica SPE confocal microscope
186 with a Plan Apo 63x NA 1.4 oil objective (HCX; Leica). Confocal software (LAS AF;
187 Leica) was used for acquisition of Z serial images, with a Plan Apo 63x NA 1.4 oil objective
188 (HCX; Leica). Confocal images presented are single-projected image derived from image
189 stacks. For all imaging, exposure settings were identical between compared samples and
190 groups. Quantifications were done as previously (48), using ImageJ software (version

191 1.46m). AChR rich-endplate area per neuromuscular junction corresponds to the occupied
192 area of α -BTX fluorescent signal. More than 20 fibres from at least five different mice of
193 each group were analysed.

194

195 Fibre size and type

196

197 Transverse serial sections (8 μ m) of TA muscles were obtained using a cryostat, in the mid-
198 belly region. Some of sections were processed for histological analysis according to standard
199 protocols (stained for Sirius red). Others were used for immunohistochemistry as described
200 (17, 38). For determination of muscle fibre diameter and myosin heavy chain (MHC)
201 analysis, frozen unfixed sections were blocked 1h in PBS plus 2% BSA, 2% sheep serum.
202 Sections were then incubated overnight with primary antibodies against laminin (rabbit
203 polyclonal, 1:300, Dako, Les Ulis, France) and myosin heavy chain (MHC) isoforms
204 (Developmental Studies Hybridoma bank, University of Iowa, USA). After washes in PBS,
205 sections were incubated 1 h with secondary antibodies (alexa fluor, Life Technologies, Saint
206 Aubin, France). For morphometric analyses images were captured using a motorized
207 confocal laser-scanning microscope (LSM 700, Carl Zeiss SAS, Le Pecq, France).
208 Morphometric analyses were made using ImageJ software and a homemade macro. The
209 smallest diameter (min Ferret) of all the muscle fibres of the whole muscle section was
210 measured. For muscle fibre diameter and fibre typing analyses all of the muscle fibres of the
211 muscle section were measured. The extent of fibrosis was assessed by Sirius red staining.

212

213 Remodeling pathways: protein

214

215 TA muscle was lysed in RIPA buffer [50 mM Tris pH 7.5, 1 % Nonident P40, 0.5 %
216 Sodium Deoxycholate, 0.1 % SDS, 150 mM NaCl, 5 mM EDTA, 1 mM
217 phenylmethanesulphonylfluoride (PMSF) and protease inhibitor cocktail (45 µg/mL, 11 873
218 580 001, Roche)] with a potter at 4°C. Homogenates (100 µg of protein) were
219 electrophoresed on 10 % polyacrylamid gels. Proteins were electroblotted to Hybond
220 nitrocellulose membranes (Amersham Biosciences) and immunodetected using primary
221 antibodies directed against Phospho-Smad1 (Ser463/465)/ Smad5 (Ser463/465)/ Smad9
222 (Ser465/467) (#13820, Cell signaling, 1/1000), FoxO1 (#2880, cell signaling, 1/1000)
223 Smad1/Smad9 (#ab108965, abcam, 1/1000), phospho-FoxO1 (Ser256) (#9461, cell
224 signaling, 1/1000), FoxO3a (#12829, cell signaling, 1/1000), phospho-FoxO3a (Ser318/321)
225 (#9465, cell signaling, 1/1000) and tubuline (IGBMC). Secondary antibodies conjugated to
226 horseradish peroxidase (Amersham Biosciences) were detected using an enhanced
227 chemiluminescence detection system (Pierce, Rockford, IL, 1/10000).

228

229 Remodeling pathways: mRNA

230

231 Total RNA from the TA muscle was isolated using TRIzol Reagent (Invitrogen). A total of 2
232 µg of RNA was reverse transcribed to cDNA with SuperScript II reverse transcriptase
233 (Invitrogen Life Technologies) and random hexamer primers according to the supplier's
234 protocol. Quantitative RT-PCR was performed by using the SYBR Green 1 marker PCR kit
235 (Roche) according to the supplier's protocol (18). The 18S ribosomal RNA was used as an
236 internal control. Primers were shown in Table 2.

237

238 Statistical analysis

239

240 Groups were generally compared using 2 way-variance analysis (castration x age, sex x age,
241 castration x genotype). If necessary, Bonferroni post-tests were also performed. For groups
242 that did not pass tests of normality and equal variance, non-parametric tests were used
243 (Kruskal Wallis and Wilcoxon). Values are means \pm SEM. Significance was set at $p < 0.05$.
244

245 Results

246

247 1-Castration reduces both absolute maximal force and power gains in male mice

248

249 We measured **the absolute maximal force** of the TA muscle in response to nerve
250 stimulation, an important aspect of muscle performance, in male mice. Castration performed
251 at 1 month of age reduced the gain in absolute maximal force between 1 month and 6
252 months. Indeed, absolute maximal force was decreased in 3- and 6-month old male castrated
253 mice (-18% and -17% respectively), as compared to age-matched intact male mice ($p <$
254 0.05)(Figure 1A). The absolute maximal force was related to the specific maximal force
255 (absolute maximal force/muscle weight), and the muscle weight (see below). We found that
256 the increase in **specific maximal force** between 1 month and 6 months was reduced by
257 castration. Specifically, specific maximal force was reduced in castrated male mice at 6
258 months of age, as compared to age-matched intact male mice (Figure 1B)($p < 0.05$).

259

260 **Absolute maximal power**, another important aspect of TA muscle performance, was also
261 measured. The gain in absolute maximal power between 1 month and 3 or 6 months
262 observed in intact male mice was reduced by castration. Absolute maximal power was
263 decreased by 30% and 18% in 3- and 6-month old castrated male mice, respectively ($p <$
264 0.05), as compared to age-matched male intact mice (Figure 1C). Absolute maximal power
265 was related to **specific maximal power**, and muscle weight (see below). We found that
266 specific maximal power was reduced in 3- and 6 month old castrated male mice, as
267 compared to age-matched male intact mice (Figure 1D)($p < 0.05$).

268

269 We also measured TA **muscle weight**, because absolute maximal force and power are

270 proportional to muscle size (muscle cross-section area and volume/weight). The gain in
271 muscle weight observed between 1 month and 3 months in intact male mice was reduced by
272 castration in male mice. Muscle weight was decreased by -16% in male castrated mice at 3
273 months of age ($p < 0.05$), as compared to age-matched male intact mice (Figure 1E).
274 However, at 6 months of age, muscle weight was similar in castrated and age-matched intact
275 male mice (Figure 1E).

276

277 Together, our results indicate that castration before puberty decreases the gains in absolute
278 maximal force and power between 1 month and 6 months of TA muscle in male mice. This
279 is due to reduced gain in specific maximal force and power, i.e. two keys aspects of muscle
280 contractile quality, and a delayed muscle growth (increase in muscle weight) in male mice.

281

282 2-Castration decreases absolute maximal force gain in female mice

283

284 Castration reduced the gain in TA **absolute maximal force** between 1 month and 3 or 6
285 months in female mice such that values were decreased in 3- and 6-month old female
286 castrated mice by -17% and -11% respectively, as compared to age-matched female intact
287 mice ($p < 0.05$)(Figure 1F). Moreover, the gain in **specific maximal force** between 1 month
288 and 6 months was reduced by castration since specific maximal force was lower in castrated
289 female mice, at 3 and 6 months of age, as compared to age-matched intact female mice
290 (Figure 1G)($p < 0.05$).

291

292 Castration did not affect the gain in TA **absolute maximal power** between 1 month and 3 or
293 6 months in female mice. Indeed, absolute maximal power was not different in 3- and 6-
294 month old female between castrated and intact mice (Figure 1H). Similarly, castration did

295 not affect specific maximal power since specific maximal power did not significantly
296 increase in 3- and 6 month old castrated female mice, as compared to age-matched female
297 intact mice ($p=0.07$)(Figure 1I).

298

299 Castration reduced the gain in TA **muscle weight** between 1 month and 3 or 6 months in
300 female mice. Indeed, female castrated mice demonstrated a reduction of 11 and 5% in
301 muscle weight at 3 and 6 months of age, respectively, as compared to age-matched intact
302 female mice (Figure 1J)($p < 0.05$).

303

304 Taken together, our results indicate that castration before puberty decreases absolute
305 maximal force of TA muscle in female mice, but not absolute maximal power. The reduced
306 absolute maximal force results from the decrease of both specific maximal force, i.e. an
307 aspect of muscle quality, and muscle weight.

308

309 3- Castration reduces sexual dimorphism regarding muscle performance

310

311 Sexual dimorphism was studied in both intact and castrated mice. We found first a sexual
312 dimorphism concerning **absolute maximal force** of TA muscle in intact mice. The absolute
313 maximal force of female intact mice was reduced (-10%) as compared to male intact mice
314 (compare Figure 1F to Figure 1A)($p < 0.05$). Secondly, in contrast, absolute maximal force
315 of female and male castrated mice did not differ (compare Figure 1F to Figure 1A).
316 Moreover, there was no sexual dimorphism regarding **specific maximal force** in intact and
317 castrated mice. Indeed, specific maximal force of intact and castrated female mice were
318 similar as compared to intact and castrated age-matched male mice (compare Figure 1G to
319 Figure 1B).

320

321 **Absolute maximal power** of the TA muscle also differed between sexes in intact mice.
322 Absolute maximal power of intact female mice was decreased (-18%), as compared to intact
323 age-matched male mice (compare Figure 1H to Figure 1C)($p < 0.05$). In contrast, the
324 absolute power of 3-month old female castrated mice was increased as compared to age-
325 matched male castrated mice (compare Figure 1H to Figure 1C)($p < 0.05$). We also found a
326 sexual dimorphism concerning **specific maximal power**, since female intact mice had a
327 lower specific maximal power, as compared to age-matched male intact mice (compare
328 Figure 1I to Figure 1D). In contrast, the specific maximal power of female castrated mice
329 was increased, as compared to age-matched male castrated mice (compare Figure 1I to
330 Figure 1D)($p < 0.05$).

331

332 Finally, there was a sexual dimorphism concerning TA **muscle weight** in intact mice.
333 Muscle weight of 3- and 6- month old female intact mice was reduced (-6%), as compared to
334 age-matched male intact mice (compare Figure 1J to Figure 1E)($p < 0.05$). Similarly, the
335 muscle weight of 6-month old castrated female castrated mice, but not 3-month old castrated
336 female mice, was decreased as compared to age-matched male castrated mice (compare
337 Figure 1J to Figure 1E)($p < 0.05$).

338

339 Together, these results indicate that in intact mice there is a sexual dimorphism concerning
340 both absolute maximal force and power of the TA muscle. The reduced muscle performance
341 in female mice is due to a decreased specific maximal force and power, i.e muscle quality,
342 and a lower muscle weight. Moreover, castration in both sexes reduces the sexual
343 dimorphism regarding absolute maximal force and power.

344

345 4- Deficiency in muscle fibre AR does not alter the effect of castration on muscle
346 performance in male mice

347

348 To determine if muscle fibre AR mediates MGRF-induced performance gain, male AR^{skm-/y}
349 mice, in which muscle fibre AR is selectively ablated, as well as male AR^{L2/y} (control)
350 littermates, were castrated at 1 month of age, and analyzed at 3 months of age. In agreement
351 with previous results (9), **absolute maximal force** of the TA muscle was lower in intact
352 AR^{skm-/y} mice than in AR^{L2/y} mice (Figure 2A)(p <0.05). Interestingly, we found that
353 absolute maximal force was similarly decreased in castrated male mice, as compared to
354 genotype-matched intact male mice, in both genotypes (-29% for AR^{skm-/y} mice and -28% for
355 AR^{L2/y} mice)(Figure 2A)(p <0.05). **Specific maximal force** was unchanged by castration in
356 both genotypes (Figure 2B). Moreover, **TA muscle weight** was similarly reduced in
357 castrated male mice (-33% for AR^{skm-/y} mice and -29% for AR^{L2/y} mice), as compared to
358 genotype-matched intact male mice (Figure 2C)(p <0.05).

359

360 Together our results indicate that muscle fibre AR deficiency does not alter the effect of
361 castration on TA muscle performance, suggesting that the action of MGRF is not mediated
362 by muscle fibre AR.

363

364 5-Reduced muscle performance is not related to altered neuromuscular transmission in 3-
365 month old castrated mice

366

367 It has been reported that androgens influence neuromuscular transmission (3). To determine
368 whether **neuromuscular transmission failure** contributes to the reduced absolute maximal
369 force in castrated mice, we also performed electrical stimulation of the TA muscle that can

370 directly initiate muscle action potentials, without the need of neuromuscular transmission (8,
371 16, 51). We found that absolute maximal force in response to nerve stimulation was
372 decreased by castration in 3-month old mice of both sexes (Figures 3A and B)($p < 0.05$),
373 confirming our previous results (Figures 1A and G). Interestingly, direct TA muscle
374 stimulation with a high strength voltage did not improve absolute maximal force in 3-month
375 old castrated mice of both sexes since there was no difference between nerve and muscle
376 stimulations (Figures 3A and B), indicating no neurotransmission failure.

377

378 To complete the analysis of neuromuscular transmission, we checked that castration does
379 not alter **neuromuscular junction morphology** in plantaris muscle fibres. Before that, we
380 confirmed that absolute maximal force and weight of the plantaris muscle were decreased in
381 3-month-old male castrated mice, as compared to age-matched intact male mice ($p <$
382 0.05)(Figure 3C). In contrast, specific maximal force was unchanged by castration (Figure
383 3C), indicating that the effects of castration on muscle performance were similar in plantaris
384 and TA muscles, at least in 3-month old male mice. Plantaris muscle fibres isolated from 3-
385 month-old castrated male mice were stained with α -BTX to detect AChR clusters and with a
386 mixture of antibodies against neurofilament and synaptophysin to label axonal branches and
387 nerves terminals, respectively. The structure of the synapse in castrated mice was
388 indistinguishable from intact ones. Indeed, all endplates analyzed formed a continuous
389 branched postnatal topology and exhibited a typical and «pretzel-like» morphology (Figure
390 3D). The fact that AChR-rich endplate area per NMJ was reduced by 30% in castrated mice
391 ($p < 0.05$)(Figure 3E) could be explained by the decreased fibre size as shown below.
392 Moreover, both in castrated and intact mice, axonal branches properly innervated the
393 postsynaptic counterpart and nerve terminals were in perfect registry with AChR clusters.
394 Quantitative analysis revealed that the synaptophysin area per NMJ (Figure 3F) as well as

395 the overlap area between pre- and postsynaptic elements (Figure 3G) were unchanged in
396 castrated mice compared to intact ones.

397

398 Taken together, these observations demonstrate that castration does not disturb NMJ
399 structure, in agreement with the observations that 3-month old castrated male mice exhibit
400 normal neuromuscular transmission, excluding the possibility that reduced performance is
401 explained by decreased muscle activation.

402

403 6-Reduced muscle performance is related to fibre atrophy and fibrosis in 3-month old
404 castrated mice

405

406 As mentioned above, part of the reduction in muscle performance is related to decreased
407 muscle weight in 3-month old castrated mice of both sexes. Therefore, we further analysed
408 the **reduced TA muscle weight** in 3-month castrated mice of both sexes (Figure 4A), as
409 previously shown (Figures 1E and J), and found that it was not associated with a decrease in
410 **bone growth** in castrated mice of both sexes. Indeed, the length of the tibia was not changed
411 by castration in both 3-month old male (17.8 ± 0.3 mm in castrated versus 18.2 ± 0.3 mm in
412 intact mice) and female (18.0 ± 0.1 mm in castrated versus 18.3 ± 0.2 mm in intact mice)
413 mice. Moreover, the reduced muscle weight in castrated mice was related to muscle **fibre**
414 **atrophy** since histological analyses revealed a left shift in the fibre diameter distribution in
415 both 3-month old castrated mice of both sexes (Figures 4BC). In line, there was an increase
416 in **fibrosis** in 3-month old castrated mice (14.2 ± 0.9 % in castrated versus 11.7 ± 2.0 % in
417 intact mice)($p < 0.05$)(Figure 4D). We also determined whether fibre atrophy was
418 accompanied by an increase in the **percentage of fibres expressing MHC-2a that** are fast
419 fibres having small fibre diameter. We found that the percentage of fibres expressing MHC-
420 2a was not modified by castration in 3-month old mice of both sexes, indicating no change

421 in fibre type composition in the muscle (Figure 4E).

422

423 Together, our results indicate that reduced muscle performance gain in 3-month old
424 castrated mice of both sexes is associated with decreased muscle fibre growth and increased
425 fibrosis but no change in fibre type composition.

426

427 7-Castration alters intramuscular remodeling pathways in 3-month old male mice

428

429 We first evaluated the activation of bone morphogenetic protein (BMP) signaling via
430 Smad1/5/9, that is an important emergent pathway controlling muscle size and performance
431 (61, 72). We investigated whether castration before puberty influences the BMP signaling
432 axis in skeletal muscle. Castration in 3 month-old male mice altered neither the amount of
433 phosphorylated Smad1/5/9 (Figures 5A and B), nor *activin-like kinase 3 (ALK3)* transcript
434 levels (Figure 5C). *Smad4* transcript levels were decreased by castration (Figure
435 5D)($p < 0.05$), but those of the downstream factor *Id1* (inhibitor of DNA binding) were
436 unaffected in castrated male mice (Figure 5E). Moreover, castration in 3-month-old female
437 mice did not alter *ALK3* (Figure 5C), *Smad4* (Figure 5D), and *Id1* (Figure 5E) transcript
438 levels ($p < 0.05$). Together, these results suggest no major change in Smad1/5/9 signaling
439 with castration in both 3-month old male and female mice.

440

441 We then determined the effect of castration on the **ubiquitin proteasome system** that plays
442 an important role in muscle physiology and atrophic process (4, 44). Castration in 3-month
443 old male mice decreased the levels of the protein phosphorylated (inactivated) form of
444 Foxo3a (Figures 6A and B), without changing that of phosphorylated Foxo1 (Figures 6A
445 and C), two transcription factors important for the regulation of E3 ubiquitin ligases.

446 Moreover, we found that the transcript levels of *Murf1* (Figure 6D) and *FbxO30* (Figure 6E)
447 were reduced in 3-month old castrated male mice, as compared to age-matched intact male
448 mice ($p < 0.05$), whereas that one of *atrogen 1* was unchanged (Figure 6F). In contrast,
449 castration did not affect the transcript levels of *Murf1*, *FbxO30* and *atrogen 1* in 3-month-
450 old female mice (Figures 6D-F). Together, these results suggest that 3-month after castration
451 E3 ubiquitin ligases (*atrogen 1*, *Murf1*, and *FbxO30*) might be less active in males and
452 unchanged in females.

453

454 In addition, we measured the transcript levels of *IGF-1* and *MSTN* (myostatin), encoding
455 proteins regulating muscle growth and function (44, 58, 66). In 3-month-old mice, castration
456 increased the transcript level of *MSTN* in males, but did not affect it in females (Figure 6G).
457 In contrast, the transcript level of *IGF-1* was unchanged in castrated males and increased in
458 castrated females (Figure 6H).

459

460 Together, our results indicate that reduced muscle performance gain is associated with
461 changes in the levels of ubiquitin ligases and *MSTN* in 3-month old male castrated mice, but
462 not in *Smad1/5/9* signaling.

463

464

465

466 Discussion

467

468 MGRF promotes long-term muscle contractile quality

469

470 Our results show that castration initiated before puberty decreased the performance of the
471 TA muscle in 6-month old male mice. Thus, MGRF, between the age of 1 month and 6
472 months, contribute to 29% and 38% of absolute maximal force and power gains,
473 respectively (Table 3). The reduced absolute maximal force and power in 6-month old
474 castrated male mice is due to a lower specific maximal force and power, but not a decreased
475 muscle weight (Table 3). Therefore, our results support the original and important notion
476 that endogenous androgens promote postnatal performance gain in 6-month old male mice
477 via the improvement/maintenance in **muscle contractile quality**, i.e. specific maximal force
478 and power, but not enhanced muscle growth. Concerning muscle growth, it is somewhat
479 unexpected that the increase in muscle weight is only delayed by castration, nuancing the
480 widespread view that androgens have an overall anabolising effect. Since in the present
481 study we studied a fast-twitch muscle, it remains to be determined whether the contractile
482 quality of a muscle with mixed fibre type composition (such as soleus muscle) is similarly
483 reduced by removal of MGRF in 6-month-old male mice. MSTN encoding myostatin can
484 also improve muscle contractile quality during postnatal development, but together with an
485 inhibition of muscle growth (45, 52, 62, 65).

486

487 Our results indicate that increased fibrosis, but not neuromuscular transmission failure, can
488 explain in part, the reduced specific maximal force and power in 6-month old castrated male
489 mice. It is possible that the decrease in muscle quality is due to accumulation of
490 nonfunctional proteins since we found that ubiquitin ligases are presumably less active in 3-

491 month old castrated male mice. It has been reported that decreased specific maximal force
492 and power are associated with reduced levels of ubiquitin ligases (44). Our results does not
493 however, relate to fibre type transition since we found no notable increase in the percentage
494 of less powerful fibre expressing MHC-2a (20), at least in 3-month old castrated male mice.
495 These data are in line with previous studies analyzing hypogonadal male mice (63). Finally,
496 decreased phosphorylation of the myosin light chains could also contribute to the reduced
497 specific maximal force, since it has been reported that acute androgen (dihydrotestosterone)
498 administration increases both specific maximal force and phosphorylation of the myosin
499 light chains (29).

500

501 MGFR are not the only factors involved in muscle performance gain

502

503 A finding of interest is that the contribution of MGRF to muscle performance gain is not
504 predominant (Table 3) since 62 to 71% of the muscle performance gains between 1 and 6
505 months are due to other factors. **Other endocrine factors** affecting muscle quality during
506 muscle development may be considered. Thyroid hormones alter fibre transition that occurs
507 during postnatal development (1, 26), and potentially affect specific maximal power since
508 fast type fibres are more powerful than slow type fibres. In mice expressing dominant
509 negative mutant IGF-1 receptors in skeletal muscle, there is a prevalence of fast fibres (68),
510 suggesting a possible effect of endocrine or local IGF-1 on specific maximal power.
511 However, we found that IGF-1 transcript levels were not modified in male castrated mice, at
512 least at the age of 3 months. Concerning growth hormone, its direct effect on muscle is
513 unlikely since muscle growth hormone receptor deficiency does not affect fibre type
514 composition in postnatal muscle (70) and it has been reported that growth hormone does not
515 alters specific maximal force (10).

516

517 The effects of MGRF on muscle performance and growth are not mediated by fibre AR and
518 BMP signaling through Smad1/5/9 phosphorylation in 3-month old male mice

519

520 Interestingly, the effect of castration before puberty on absolute maximal force gain is not
521 abolished in the **absence of muscle fibre AR**, at least in 3-month old male mice. At the age
522 of 3 months, the reduced absolute maximal force in castrated male mice resulted from a
523 **lower muscle weight** and fibre atrophy. These results suggest that the action of endogenous
524 androgens on muscle performance gain and growth is not mediated by muscle fibre AR, at
525 least in 3-month old male mice. These findings extend those of a previous study showing
526 that 1 month-castration performed in the adult stage similarly decreased muscle weight in
527 deficient or non-deficient muscle fibre AR male mice (9). In accordance, it has been
528 reported that the postnatal development of hindlimb muscle is independent from fibre AR
529 signaling in mice (9, 13, 55).

530

531 Many other cells express AR, in particular satellite cells. However, in the present study, the
532 possibility that androgen effect on muscle weight is mediated via the AR of satellite cells is
533 unlikely since satellite cells do not contribute to muscle growth after the age of 3 weeks.
534 Indeed, there is no further myonuclei addition at this postnatal stage in mice (71). A
535 possibility is that androgen effect on muscle growth can be mediated via AR localized in the
536 brain. This hypothesis is supported by the facts that: (i) the level of voluntary exercise in
537 male animals is negatively and positively modulated by castration and androgen
538 administration, respectively (14, 35) and (ii) reduced activity alters muscle performance and
539 size (31).

540

541 Another possibility is that other endocrine/paracrine factors mediate the effect of androgens
542 on muscle weight. Indeed, testosterone can be converted to estrogens by aromatase, and
543 estrogens are known to affect muscle physiology (FGRF, see below). GH and IGF-1 are
544 unlikely since it has been reported that the circulating GH and IGF-1 are not mandatory for
545 mediating the effect of androgens, at least in highly androgen responsible muscle from adult
546 male mice (64). Several recent studies reported that androgens interact with MSTN, a
547 member of the transforming growth factor-beta (TGF β) superfamily, in skeletal muscle (5,
548 12, 46, 65). In line, we found that the transcript level of MSTN was increased by castration
549 in 3-month-old male mice. Since inactivation of MSTN increases muscle growth (62, 66),
550 the higher expression of MSTN in castrated male mice can explain muscle atrophy.

551

552 Another member of the (TGF β) superfamily, BMP signaling through Smad1/5/9
553 phosphorylation is an emergent pathway controlling muscle size (61, 72). Indeed, it has been
554 suggested that BMP signaling participates in postnatal muscle development, since the
555 phosphorylation of Smad1/5/9 is lower in 6-month old (adult) mice as compared to younger
556 mice (72). BMPs are proteins that bind to BMP receptor, such as ALK3, that in turn
557 phosphorylates Smad1/5/9 proteins, promoting with *Smad4*, the regulation of target genes,
558 in particular *Id1* and various processes regulating muscle size (60). However, our data
559 provide initial insights that the delayed muscle growth in 3-month old castrated mice is not
560 likely to be related to changes in BMP signaling through Smad1/5/9 phosphorylation. The
561 **ubiquitin proteasome system** also plays an important role in the atrophic process (4).
562 However, in contrast to increased MSTN expression, the likely less active ubiquitin ligases
563 cannot explain the reduced weight in 3-month old castrated male mice.

564

565 Differential effect of FGRF versus MGFR on muscle performance gain

566

567 Another novel finding of our study is that, in contrast to MGRF in male mice, **FGRF does**
568 **not contribute to maximal power gain** between 1 month and 6 months in female mice
569 (Table 3). However **FGRF contribute to 20% of maximal force gain** in 6-month old
570 female mice (Table 3), similarly to MGFR in male mice, and its action is irrespective of any
571 change in neurotransmission. These results differ, for yet unknown reasons, from those of
572 previous studies showing that castration increases or has no effect on absolute maximal
573 force in growing female rats (42, 67). In line with our results, it has been shown that
574 estrogens positively modulate absolute maximal force in adult female mice (24, 49, 50).
575 Indeed, castration reduces **specific maximal** force and maximal calcium activated force of
576 permeabilized fibres in adult female mice, and this effect is explained by a lower fraction of
577 myosin heads strongly bound to actin (49, 50).

578

579 Together with the reduced specific maximal force, i.e muscle quality, a lower muscle weight
580 explains the effect of castration on the absolute maximal force in 3- and 6-month old female
581 mice. Thus, in contrast to MGRF, we found that FGRF also contributes to the **increase in**
582 **muscle weight** during postnatal development, even though its contribution is rather small
583 (12%)(Table 3). Our results also demonstrate that FGRF promotes the growth of muscle
584 fibres, in agreement with a recent study (39). However, this fibre growth is not related to
585 changes in MSTN, BMP signaling through Smad1/5/9 phosphorylation and ubiquitin
586 ligases, at least in 3-month old female mice. The increased transcript level of IGF-1, a factor
587 promoting muscle growth, in 3-month old castrated female mice could be a compensatory
588 phenomenon. It is possible that impaired intrinsic function of satellite cells (39) contributes
589 to the reduced muscle growth observed after castration in female mice.

590

591 It also remains to be confirmed whether the action of putative endogenous estrogens on
592 absolute maximal force is mediated via estrogen receptor (ER) that exhibits different
593 subtypes, ER α , ER β and Gper. It was reported that estrogen effects on muscle are mediated
594 in part via muscle ER α in mice (6, 54). In accordance, ER β deficiency does not lead to
595 significant change in absolute maximal force (23). However, a recent study demonstrated
596 that estrogens have a rapid effect on muscle contractility via both ER β and Gper (40), e.g.,
597 the potentiated force was increased. There is a possibility that estrogen effects can be
598 mediated by brain ER since estrogens increase the level of voluntary exercise (14, 21) which
599 is known to modulate muscle performance and growth. In agreement, a recent study
600 suggests that castration-induced muscle atrophy could result from the reduced level of motor
601 activity in adult female mice (21). However, it has been reported that the benefits of
602 estrogens is independent of physical activity, e.g. can be observed in inactive muscle (24). In
603 summary, we demonstrate that FGRF play a role in maximal force gain and muscle mass
604 development, contrasting the traditional view that estrogens have no impact on muscle
605 postnatal development. The signaling axis through which these effects are mediated is still
606 not well defined.

607

608 Sexual dimorphism concerning muscle performance is reduced by castration

609

610 We also report several differences between sexes concerning muscle performance at 6
611 months of age, in intact mice. The reduced absolute maximal force in 6-month intact female
612 mice, as compared to males, is explained by a **lower muscle weight**, in line with previous
613 studies, without difference in specific maximal force (62). Our results suggest that the lower
614 muscle weight in female mice is related to sex-based difference in *IGF-1* gene expression
615 (lower transcript level in female) but not BMP signaling, ubiquitin ligases and *MSTN* gene

616 expression. Regarding absolute maximal power, we found that the lowered absolute
617 maximal power in 6-month old female intact mice results from both reductions in **specific**
618 **maximal power** and muscle weight, as previously shown (62). We report here that reduced
619 specific maximal power is not related to an increased percentage of less powerful fibres
620 expressing MHC-2a. It is possible that the increased fibrosis in female mice contributes, at
621 least in part, to the reduced specific maximal power.

622

623 Another novel finding of our study is that castration before puberty reduces the sexual
624 dimorphism concerning both absolute maximal force and power in 6-month old mice,
625 indicating that MGRF and FGRF contribute to the sex-based differences regarding muscle
626 performance. Concerning the **lower muscle weight** that explains the lower absolute
627 maximal force and power in intact female mice, we found that castration does not fully
628 eliminate this sex-based difference, suggesting that both endogenous sexual hormones and
629 other additional factors can contribute to this aspect, such as MSTN (43) or IGF-1. In line,
630 we found a sex-based difference in MSTN mRNA level in castrated mice. The **lower**
631 **specific maximal power** in intact female mice is reversed by castration (increased specific
632 maximal power in castrated females versus castrated males), suggesting that MGRF and
633 FGRF have beneficial and detrimental actions on specific maximal power, respectively. Our
634 results indicate that these effects cannot be attributed to a sex-based difference in fibre type
635 specification in castrated mice, a finding that adds to an equivocal body of evidence
636 regarding the respective effects of androgens and estrogens on muscle fibre type
637 specification (2, 27, 39, 53, 56, 63).

638

639 Conclusion

640

641 In summary, our study indicates that MGRF promotes muscle absolute maximal force and
642 power gains between 1 month and 6 months in male mice, mainly via promoting muscle
643 contractile quality, and without affecting neuromuscular transmission. In 3-month old male
644 mice, the effects of MGRF on muscle performance are not mediated by muscle fibre AR. In
645 female mice, FGRF promotes absolute maximal force gain between 1 month and 6 months
646 but not absolute maximal power gain. Here we provide preliminary insights that demonstrate
647 that the effects of MGRF and FGRF in 3-month old mice are not related to alterations in
648 BMP signaling through Smad1/5/9. However, our results suggest that the action of MGRF
649 could be mediated via the upregulation of ubiquitin ligases in 3-month old male mice. Now,
650 more protracted efforts are needed to define the signaling cascades responsible for the
651 effects of sex-related hormones. We also show that MGRF and FGRF only marginally
652 contribute to muscle performance gain between 1 month and 6 months of age in both sexes,
653 indicating the existence of additional factors, endocrine or not. Finally, we have
654 demonstrated that MGRF and FGRF contribute to the sexual dimorphism regarding muscle
655 performance in adult mice. Thus, we provide evidence demonstrating that both MGRF and
656 FGRF are required for the normal postnatal development of muscle performance in mice of
657 both sexes.

658

659 Acknowledgements

660

661 We are grateful to Juliette Breuil, Arthur Cetaire, Antoine Espagnol, Saad Idrissi-Zougari
662 (Université Paris Descartes) and Rémi Thomasson (Institut de Recherche biomédicale et
663 d'épidémiologie du Sport, Université Paris Descartes) for assistance during the experiments.
664 We also thank Stéphanie Bauché and Laure Stochlic (Université Pierre et Marie Curie) for
665 synaptophysin antibody and technical advice.

666

667 Funding

668

669 Financial support has been provided by Université Pierre et Marie Curie (UPMC), CNRS,
670 INSERM, ANR AndroGluco, FRM (FDT20150532221) University Paris Descartes,
671 Université de Strasbourg, IGBMC, the Association Française contre les Myopathies (AFM).
672 and by French state through the Agence Nationale de la Recherche ANR-10-LABX-0030-
673 INRT under the frame programme Investissements d’Avenir labelled ANR-10-IDEX-0002-
674 02. V.U-P was supported by the Fondation pour la Recherche Médicale

675

676

677 Declaration of interest

678

679 The authors declare that there is no conflict of interest that could be perceived as prejudicing
680 the impartiality of the research reported.

681

682 Author contributions

683

684 DM and AF conceived the research.

685 VUP, JM, ML, PR and AF performed experiments and analysed data.

686 AS, DJO, PN and OA provided expertise.

687 VUP, DM and AF wrote the manuscript.

688 All authors edited and approved the manuscript.

689

690

691 References

692

- 693 1. **Agbulut O, Noirez P, Beaumont F, Butler-Browne G.** Myosin heavy chain isoforms
694 in postnatal muscle development of mice. *Biol Cell* 95: 399–406, 2003.
- 695 2. **Axell AM, MacLean HE, Plant DR, Harcourt LJ, Davis JA, Jimenez M,**
696 **Handelsman DJ, Lynch GS, Zajac JD.** Continuous testosterone administration
697 prevents skeletal muscle atrophy and enhances resistance to fatigue in orchidectomized
698 male mice. *Am J Physiol Endocrinol Metab* 291: E506-16, 2006.
- 699 3. **Blanco CE, Zhan WZ, Fang YH, Sieck GC.** Exogenous testosterone treatment
700 decreases diaphragm neuromuscular transmission failure in male rats. *J Appl Physiol*
701 *Bethesda Md* 1985 90: 850–856, 2001.
- 702 4. **Bodine SC, Baehr LM.** Skeletal muscle atrophy and the E3 ubiquitin ligases MuRF1
703 and MAFbx/atrogen-1. *Am J Physiol Endocrinol Metab* 307: E469-484, 2014.
- 704 5. **Braga M, Bhasin S, Jasuja R, Pervin S, Singh R.** Testosterone inhibits transforming
705 growth factor-beta signaling during myogenic differentiation and proliferation of
706 mouse satellite cells: potential role of follistatin in mediating testosterone action. *Mol*
707 *Cell Endocrinol* 350: 39–52, 2013.
- 708 6. **Brown M, Ning J, Ferreira JA, Bogener JL, Lubahn DB.** Estrogen receptor-alpha
709 and -beta and aromatase knockout effects on lower limb muscle mass and contractile
710 function in female mice. *Am J Physiol Endocrinol Metab* 296: E854-861, 2009.
- 711 7. **Bunratsami S, Udomuksorn W, Kumarnsit E, Vongvatcharanon S,**
712 **Vongvatcharanon U.** Estrogen replacement improves skeletal muscle performance by
713 increasing parvalbumin levels in ovariectomized rats. *Acta Histochem* 117: 163–175,
714 2015.
- 715 8. **Cairns SP, Taberner AJ, Loiselle DS.** Changes of surface and t-tubular membrane
716 excitability during fatigue with repeated tetani in isolated mouse fast- and slow-twitch
717 muscle. *J Appl Physiol* 1985 106: 101–12, 2009.
- 718 9. **Chambon C, Duteil D, Vignaud A, Ferry A, Messaddeq N, Malivindi R, Kato S,**
719 **Chambon P, Metzger D.** Myocytic androgen receptor controls the strength but not the
720 mass of limb muscles. *Proc Natl Acad Sci U A* 107: 14327–32, 2010.
- 721 10. **Chikani V, Ho KKY.** Action of GH on skeletal muscle function: molecular and
722 metabolic mechanisms. *J Mol Endocrinol* 52: R107-123, 2014.
- 723 11. **De Naeyer H, Lamon S, Russell AP, Everaert I, De Spaey A, Vanheel B, Taes Y,**
724 **Derave W.** Androgenic and estrogenic regulation of Atrogen-1, MuRF1 and myostatin
725 expression in different muscle types of male mice. *Eur J Appl Physiol* 114: 751–761,
726 2014.
- 727 12. **Dubois V, Laurent M, Boonen S, Vanderschueren D, Claessens F.** Androgens and
728 skeletal muscle: cellular and molecular action mechanisms underlying the anabolic
729 actions. *Cell Mol Life Sci* 69: 1651–67, 2013.

- 730 13. **Dubois V, Laurent MR, Sinnesael M, Cielen N, Helsen C, Clinckemalie L, Spans L,**
731 **Gayán-Ramirez G, Deldicque L, Hespel P, Carmeliet G, Vanderschueren D,**
732 **Claessens F.** A satellite cell-specific knockout of the androgen receptor reveals
733 myostatin as a direct androgen target in skeletal muscle. *Faseb J* 28: 2979–94, 2014.
- 734 14. **Ferreira JA, Foley AM, Brown M.** Sex hormones differentially influence voluntary
735 running activity, food intake and body weight in aging female and male rats. *Eur J*
736 *Appl Physiol* 112: 3007–3018, 2012.
- 737 15. **Ferry A, Benchaouir R, Joanne P, Peat RA, Mougnot N, Agbulut O, Butler-**
738 **Browne G.** Effect of voluntary physical activity initiated at age 7 months on skeletal
739 hindlimb and cardiac muscle function in mdx mice of both genders. *Muscle Nerve* 52:
740 788–794, 2015.
- 741 16. **Ferry A, Joanne P, Hadj-Said W, Vignaud A, Lilienbaum A, Hourdé C, Medja F,**
742 **Noirez P, Charbonnier F, Chatonnet A, Chevessier F, Nicole S, Agbulut O,**
743 **Butler-Browne G.** Advances in the understanding of skeletal muscle weakness in
744 murine models of diseases affecting nerve-evoked muscle activity, motor neurons,
745 synapses and myofibers. *Neuromuscul Disord NMD* 24: 960–972, 2014.
- 746 17. **Ferry A, Parlakian A, Joanne P, Fraysse B, Mgrditchian T, Roy P, Furling D,**
747 **Butler-Browne G, Agbulut O.** Mechanical Overloading Increases Maximal Force and
748 Reduces Fragility in Hind Limb Skeletal Muscle from Mdx Mouse. *Am J Pathol* 185:
749 2012–24, 2015.
- 750 18. **Ferry A, Schuh M, Parlakian A, Mgrditchian T, Valnaud N, Joanne P, Butler-**
751 **Browne G, Agbulut O, Metzger D.** Myofiber androgen receptor promotes maximal
752 mechanical overload-induced muscle hypertrophy and fiber type transition in male
753 mice. *Endocrinology* 155: 4739–4748, 2014.
- 754 19. **Fiorotto ML, Davis TA, Sosa HA, Villegas-Montoya C, Estrada I, Fleischmann R.**
755 Ribosome abundance regulates the recovery of skeletal muscle protein mass upon
756 recuperation from postnatal undernutrition in mice. *J Physiol* 592: 5269–5286, 2014.
- 757 20. **Fitts RH, Widrick JJ.** Muscle mechanics: adaptations with exercise-training. *Exerc*
758 *Sport Sci Rev* 24: 427–473, 1996.
- 759 21. **Fonseca H, Powers SK, Gonçalves D, Santos A, Mota MP, Duarte JA.** Physical
760 inactivity is a major contributor to ovariectomy-induced sarcopenia. *Int J Sports Med*
761 33: 268–278, 2012.
- 762 22. **Fraysse B, Vignaud A, Fane B, Schuh M, Butler-Browne G, Metzger D, Ferry A.**
763 Acute effect of androgens on maximal force-generating capacity and electrically
764 evoked calcium transient in mouse skeletal muscles. *Steroids* 87: 6–11, 2014.
- 765 23. **Glenmark B, Nilsson M, Gao H, Gustafsson J-A, Dahlman-Wright K, Westerblad**
766 **H.** Difference in skeletal muscle function in males vs. females: role of estrogen
767 receptor-beta. *Am J Physiol Endocrinol Metab* 287: E1125-1131, 2004.
- 768 24. **Greising SM, Baltgalvis KA, Kosir AM, Moran AL, Warren GL, Lowe DA.**
769 Estradiol's beneficial effect on murine muscle function is independent of muscle
770 activity. *J Appl Physiol Bethesda Md* 1985 110: 109–115, 2011.

- 771 25. **Greising SM, Carey RS, Blackford JE, Dalton LE, Kosir AM, Lowe DA.** Estradiol
772 treatment, physical activity, and muscle function in ovarian-senescent mice. *Exp*
773 *Gerontol* 46: 685–93, 2011.
- 774 26. **Haddad F, Arnold C, Zeng M, Baldwin K.** Interaction of thyroid state and denervation
775 on skeletal myosin heavy chain expression. *Muscle Nerve* 20: 1487–1496, 1997.
- 776 27. **Haizlip KM, Harrison BC, Leinwand LA.** Sex-based differences in skeletal muscle
777 kinetics and fiber-type composition. *Physiol Bethesda Md* 30: 30–39, 2015.
- 778 28. **Hakim CH, Duan D.** Gender differences in contractile and passive properties of mdx
779 extensor digitorum longus muscle. *Muscle Nerve* 45: 250–6, 2012.
- 780 29. **Hamdi MM, Mutungi G.** Dihydrotestosterone activates the MAPK pathway and
781 modulates maximum isometric force through the EGF receptor in isolated intact mouse
782 skeletal muscle fibres. *J Physiol* 588: 511–525, 2010.
- 783 30. **Hourde C, Jagerschmidt C, Clement-Lacroix P, Vignaud A, Ammann P, Butler-**
784 **Browne GS, Ferry A.** Androgen replacement therapy improves function in male rat
785 muscles independently of hypertrophy and activation of the Akt/mTOR pathway. *Acta*
786 *Physiol* 195: 471–82, 2009.
- 787 31. **Hourde C, Joanne P, Medja F, Mougnot N, Jacquet A, Mouisel E, Pannerec A,**
788 **Hatem S, Butler-Browne G, Agbulut O, Ferry A.** Voluntary Physical Activity
789 Protects from Susceptibility to Skeletal Muscle Contraction-Induced Injury But
790 Worsens Heart Function in mdx Mice. *Am J Pathol* 182: 1509–18, 2013.
- 791 32. **Hourde C, Joanne P, Noirez P, Agbulut O, Butler-Browne G, Ferry A.** Protective
792 effect of female gender-related factors on muscle force-generating capacity and
793 fragility in the dystrophic mdx mouse. *Muscle Nerve* 48: 68–75, 2013.
- 794 33. **Hourde C, Joanne P, Noirez P, Agbulut O, Butler-Browne G, Ferry A.** Protective
795 effect of female gender-related factors on muscle force-generating capacity and
796 fragility in the dystrophic mdx mouse. *Muscle Nerve* 48: 68–75, 2013.
- 797 34. **Hunter SK.** Sex Differences and Mechanisms of Task-Specific Muscle Fatigue. *Exerc*
798 *Sport Sci Rev* 37: 113–122, 2009.
- 799 35. **Ibebunjo C, Eash JK, Li C, Ma Q, Glass DJ.** Voluntary running, skeletal muscle gene
800 expression, and signaling inversely regulated by orchidectomy and testosterone
801 replacement. *Am J Physiol Endocrinol Metab* 300: E327-40, 2011.
- 802 36. **James RS, Young IS, Cox VM, Goldspink DF, Altringham JD.** Isometric and
803 isotonic muscle properties as determinants of work loop power output. *Pflugers Arch*
804 432: 767–774, 1996.
- 805 37. **Jiao Q, Pruznak AM, Huber D, Vary TC, Lang CH.** Castration differentially alters
806 basal and leucine-stimulated tissue protein synthesis in skeletal muscle and adipose
807 tissue. *Am J Physiol Endocrinol Metab* 297: E1222-1232, 2009.
- 808 38. **Joanne P, Hourde C, Ochala J, Cauderan Y, Medja F, Vignaud A, Mouisel E,**
809 **Hadj-Said W, Arandel L, Garcia L, Goyenvalle A, Mounier R, Zibroba D,**

- 810 **Sakamoto K, Butler-Browne G, Agbulut O, Ferry A.** Impaired adaptive response to
811 mechanical overloading in dystrophic skeletal muscle. *PLoS One* 7: e35346, 2012.
- 812 39. **Kitajima Y, Ono Y.** Estrogens maintain skeletal muscle and satellite cell functions. *J*
813 *Endocrinol* 229: 267–275, 2016.
- 814 40. **Lai S, Collins BC, Colson BA, Kararigas G, Lowe DA.** Estradiol modulates myosin
815 regulatory light chain phosphorylation and contractility in skeletal muscle of female
816 mice. *Am J Physiol Endocrinol Metab* 310: E724-733, 2016.
- 817 41. **Lowe DA, Baltgalvis KA, Greising SM.** Mechanisms behind Estrogens' Beneficial
818 Effect on Muscle Strength in Females. *Exerc Sport Sci Rev* 38: 61–67, 2010.
- 819 42. **McCormick KM, Burns KL, Piccone CM, Gosselin LE, Brazeau GA.** Effects of
820 ovariectomy and estrogen on skeletal muscle function in growing rats. *J Muscle Res*
821 *Cell Motil* 25: 21–27, 2004.
- 822 43. **McMahon CD, Popovic L, Jeanplong F, Oldham JM, Kirk SP, Osepchook CC,**
823 **Wong KW, Sharma M, Kambadur R, Bass JJ.** Sexual dimorphism is associated
824 with decreased expression of processed myostatin in males. *Am J Physiol Endocrinol*
825 *Metab* 284: E377-81, 2003.
- 826 44. **Mendias CL, Kayupov E, Bradley JR, Brooks SV, Claflin DR.** Decreased specific
827 force and power production of muscle fibers from myostatin-deficient mice are
828 associated with a suppression of protein degradation. *J Appl Physiol* 111: 185–91,
829 2011.
- 830 45. **Mendias CL, Marcin JE, Calderon DR, Faulkner JA.** Contractile properties of EDL
831 and soleus muscles of myostatin-deficient mice. *J Appl Physiol* 101: 898–905, 2006.
- 832 46. **Mendler L, Baka Z, Kovacs-Simon A, Dux L.** Androgens negatively regulate
833 myostatin expression in an androgen-dependent skeletal muscle. *Biochem Biophys Res*
834 *Commun* 361: 237–42, 2007.
- 835 47. **Messéant J, Dobbertin A, Girard E, Delers P, Manuel M, Mangione F, Schmitt A,**
836 **Le Denmat D, Molgó J, Zytnicki D, Schaeffer L, Legay C, Strohlic L.** MuSK
837 frizzled-like domain is critical for mammalian neuromuscular junction formation and
838 maintenance. *J Neurosci Off J Soc Neurosci* 35: 4926–4941, 2015.
- 839 48. **Messéant J, Dobbertin A, Girard E, Delers P, Manuel M, Mangione F, Schmitt A,**
840 **Le Denmat D, Molgó J, Zytnicki D, Schaeffer L, Legay C, Strohlic L.** MuSK
841 Frizzled-Like Domain Is Critical for Mammalian Neuromuscular Junction Formation
842 and Maintenance. *J Neurosci Off J Soc Neurosci* 35: 4926–4941, 2015.
- 843 49. **Moran AL, Nelson SA, Landisch RM, Warren GL, Lowe DA.** Estradiol replacement
844 reverses ovariectomy-induced muscle contractile and myosin dysfunction in mature
845 female mice. *J Appl Physiol Bethesda Md* 1985 102: 1387–1393, 2007.
- 846 50. **Moran AL, Warren GL, Lowe DA.** Removal of ovarian hormones from mature mice
847 detrimentally affects muscle contractile function and myosin structural distribution. *J*
848 *Appl Physiol Bethesda Md* 1985 100: 548–559, 2006.

- 849 51. **Mouisel E, Blondet B, Escourrou P, Chatonnet A, Molgó J, Ferry A.** Outcome of
850 acetylcholinesterase deficiency for neuromuscular functioning. *Neurosci Res* 55: 389–
851 396, 2006.
- 852 52. **Mouisel E, Relizani K, Mille-Hamard L, Denis R, Hourdé C, Agbulut O, Patel K,**
853 **Arandel L, Morales-Gonzalez S, Vignaud A, Garcia L, Ferry A, Luquet S, Billat**
854 **V, Ventura-Clapier R, Schuelke M, Amthor H.** Myostatin is a key mediator between
855 energy metabolism and endurance capacity of skeletal muscle. *Am J Physiol Regul*
856 *Integr Comp Physiol* 307: R444-454, 2014.
- 857 53. **Noirez P, Ferry A.** Effect of anabolic/androgenic steroids on myosin heavy chain
858 expression in hindlimb muscles of male rats. *Eur J Appl Physiol* 81: 155–8, 2000.
- 859 54. **Ogawa M, Kitakaze T, Harada N, Yamaji R.** Female-specific regulation of skeletal
860 muscle mass by USP19 in young mice. *J Endocrinol* 225: 135–145, 2015.
- 861 55. **Ophoff J, Van Proeyen K, Callewaert F, De Gendt K, De Bock K, Vanden Bosch A,**
862 **Verhoeven G, Hespel P, Vanderschueren D.** Androgen signaling in myocytes
863 contributes to the maintenance of muscle mass and fiber type regulation but not to
864 muscle strength or fatigue. *Endocrinology* 150: 3558–3566, 2009.
- 865 56. **Piccone CM, Brazeau GA, McCormick KM.** Effect of oestrogen on myofibre size and
866 myosin expression in growing rats. *Exp Physiol* 90: 87–93, 2005.
- 867 57. **Pinter O, Beda Z, Csaba Z, Gerendai I.** Differences in the onset of puberty in selected
868 inbred mouse strains. *Endocr Abstr* 14: 617, 2007.
- 869 58. **Qaisar R, Renaud G, Morine K, Barton ER, Sweeney HL, Larsson L.** Is functional
870 hypertrophy and specific force coupled with the addition of myonuclei at the single
871 muscle fiber level? *Faseb J* 26: 1077–85, 2012.
- 872 59. **Roy P, Rau F, Ochala J, Messéant J, Fraysse B, Lainé J, Agbulut O, Butler-Browne**
873 **G, Furling D, Ferry A.** Dystrophin restoration therapy improves both the reduced
874 excitability and the force drop induced by lengthening contractions in dystrophic mdx
875 skeletal muscle. *Skelet Muscle* 6: 23, 2016.
- 876 60. **Sartori R, Sandri M.** Bone and morphogenetic protein signalling and muscle mass.
877 *Curr Opin Clin Nutr Metab Care* 18: 215–220, 2015.
- 878 61. **Sartori R, Schirwis E, Blaauw B, Bortolanza S, Zhao J, Enzo E, Stantzou A,**
879 **Mouisel E, Toniolo L, Ferry A, Stricker S, Goldberg AL, Dupont S, Piccolo S,**
880 **Amthor H, Sandri M.** BMP signaling controls muscle mass. *Nat Genet* 45: 1309–
881 1318, 2013.
- 882 62. **Schirwis E, Agbulut O, Vadrot N, Mouisel E, Hourde C, Bonniou A, Butler-Browne**
883 **G, Amthor H, Ferry A.** The beneficial effect of myostatin deficiency on maximal
884 muscle force and power is attenuated with age. *Exp Gerontol* 48: 183–90, 2013.
- 885 63. **Sciote JJ, Horton MJ, Zyman Y, Pascoe G.** Differential effects of diminished
886 oestrogen and androgen levels on development of skeletal muscle fibres in
887 hypogonadal mice. *Acta Physiol Scand* 172: 179–187, 2001.

- 888 64. **Serra C, Bhasin S, Tangherlini F, Barton ER, Ganno M, Zhang A, Shansky J,**
889 **Vandenburgh HH, Travison TG, Jasuja R, Morris C.** The role of GH and IGF-I in
890 mediating anabolic effects of testosterone on androgen-responsive muscle.
891 *Endocrinology* 152: 193–206, 2011.
- 892 65. **Stantzou A, Ueberschlag-Pitiot V, Thomasson R, Furling D, Bonniou A, Amthor H,**
893 **Ferry A.** The effect of constitutive inactivation of the myostatin gene on the gain in
894 muscle strength during postnatal growth in two murine models. *Muscle Nerve* (June
895 16, 2016). doi: 10.1002/mus.25220.
- 896 66. **Stantzou A, Ueberschlag-Pitiot V, Thomasson R, Furling D, Bonniou A, Amthor H,**
897 **Ferry A.** Effect of constitutive inactivation of the myostatin gene on the gain in muscle
898 strength during postnatal growth in two murine models. *Muscle Nerve* 55: 254–261,
899 2017.
- 900 67. **Suzuki S, Yamamuro T.** Long-term effects of estrogen on rat skeletal muscle. *Exp*
901 *Neurol* 87: 291–299, 1985.
- 902 68. **Vaitheesvaran B, LeRoith D, Kurland IJ.** MKR mice have increased dynamic glucose
903 disposal despite metabolic inflexibility, and hepatic and peripheral insulin insensitivity.
904 *Diabetologia* 53: 2224–2232, 2010.
- 905 69. **Vignaud A, Hourde C, Medja F, Agbulut O, Butler-Browne G, Ferry A.** Impaired
906 skeletal muscle repair after ischemia-reperfusion injury in mice. *J Biomed Biotechnol*
907 2010: 724914, 2010.
- 908 70. **Vijayakumar A, Buffin NJ, Gallagher EJ, Blank J, Wu Y, Yakar S, LeRoith D.**
909 Deletion of growth hormone receptors in postnatal skeletal muscle of male mice does
910 not alter muscle mass and response to pathological injury. *Endocrinology* 154: 3776–
911 3783, 2013.
- 912 71. **White RB, Bierinx AS, Gnocchi VF, Zammit PS.** Dynamics of muscle fibre growth
913 during postnatal mouse development. *BMC Dev Biol* 10: 21, 2010.
- 914 72. **Winbanks CE, Chen JL, Qian H, Liu Y, Bernardo BC, Beyer C, Watt KI,**
915 **Thomson RE, Connor T, Turner BJ, McMullen JR, Larsson L, McGee SL,**
916 **Harrison CA, Gregorevic P.** The bone morphogenetic protein axis is a positive
917 regulator of skeletal muscle mass. *J Cell Biol* 203: 345–357, 2013.
- 918
- 919

920 Legends of figures

921

922 Figure 1. Muscle performance in castrated male and female mice (TA muscle).

923 A: Absolute maximal force in male mice. B: Specific maximal force in male mice. C:

924 Absolute maximal power in male mice. D: Specific maximal power in male mice. E: Muscle

925 weight in male mice. F: Absolute maximal force in female mice. G: Specific maximal force

926 in female mice. H: Absolute maximal power in female mice. I: Specific maximal power in

927 female mice. J: Muscle weight in female mice.

928 1m : 1-month old ; 1.5 : 1.5-month old ; 3m : 3-month old; 6m : 6-month old ; cas :

929 castrated.

930 c : Castrated mice different from corresponding intact mice ($p < 0.05$).

931 s : Female mice different from corresponding male mice ($p < 0.05$).

932 n=8-16/group;

933 The data in the figure were collected during the first set of measurements, in the same mice.

934

935 Figure 2. Muscle performance in 3-month old castrated male mice with deficiency in muscle

936 fibre AR (TA muscle).

937 A: Absolute maximal force. B: Specific maximal force. C: Muscle weight.

938 $AR^{L2/y}$: Wild-type mice. $AR^{skm/-y}$: Mice with muscle fibre AR deficiency.

939 c : Castrated mice different from corresponding intact mice ($p < 0.05$).

940 n=6-8/group

941 The data in the figure were collected during the second set of measurements, in the same

942 mice.

943

944

945 Figure 3. Neuromuscular transmission and neuromuscular junction morphology in 3-month
946 old castrated mice.

947 A: Absolute maximal force in response to nerve or muscle stimulation in male mice (TA
948 muscle). B: Absolute maximal force in response to nerve or muscle stimulation in female
949 mice (TA muscle). C: Absolute and specific maximal forces and weight of plantaris muscle
950 (male mice). D: Representative images of neuromuscular junction in castrated male mice
951 (plantaris muscle). Scale bar = 20 μm . E: AChR-rich endplate area (plantaris muscle, male
952 mice). F: pre/post overlap (plantaris muscle, male mice). G: Synaptophysin area (plantaris
953 muscle, male mice).

954 c : Castrated mice different from corresponding intact mice ($p < 0.05$).

955 n=9-14/group for A-C; n=20/group for D-G.

956 The data in the figure were collected during the third set of measurements, in the same mice.

957

958

959 Figure 4: Muscle and fibre atrophy, and fibre type composition in 3-month old male and
960 female castrated mice (TA muscle).

961 A: Muscle weight. B: Distribution of diameter (min ferret) of fibres in castrated male mice,
962 using histological analysis. C: Distribution of diameter (min ferret) of fibres in castrated
963 female mice. D: Fibrosis using histological red Sirius staining. E: Percentage of fibres
964 expressing MHC-2a, using immunohistological staining.

965 c : Castrated mice different from corresponding intact mice ($p < 0.05$).

966 s : Female mice different from corresponding male mice ($p < 0.05$).

967 n=10-14 per group for A; n=3-4 per group for B-E.

968 The data in the figure were collected during the third set of measurements, in the same mice.

969

970 Figure 5. Intramuscular remodeling pathway: markers of BMP signaling through Smad1/5/9
971 in 3-month old castrated male and female mice (TA muscle).

972 A : Representative images of Western blots (male mice). B : Protein levels of
973 phosphorylated Smad1/5/9 (male mice). C: mRNA levels of ALK3. D: mRNA levels of
974 Smad4. E: mRNA levels of ID1.

975 Int : intact ; Cas : castrated.

976 c : Castrated mice different from corresponding intact mice ($p < 0.05$).

977 s : Female mice different from corresponding male mice ($p < 0.05$).

978 $n=5-7$ per group.

979 The data in the figure were collected during the third set of measurements, in the same mice.

980

981 Figure 6. Intramuscular remodeling pathway: markers of the ubiquitin proteasome system,
982 and IGF-1 and MSTN transcript levels in 3-month old castrated male and female mice (TA
983 muscle).

984 A : Representative images of blots (male mice). B : Protein levels of phosphorylated Foxo3a
985 (male mice). C : Protein level of phosphorylated Foxo1 (male mice). D: mRNA levels of
986 Murf1. E : mRNA levels of FbxO30. F : mRNA levels of atrogen 1. G : mRNA levels of
987 MSTN. H: mRNA levels of IGF-1.

988 Int : intact ; Cas : castrated ; IGF-1 : insulin growth factor 1 ; MSTN : myostatin.

989 c : Castrated mice different from corresponding intact mice ($p < 0.05$).

990 s : Female mice different from corresponding male mice ($p < 0.05$).

991 $n=5-7$ /group.

992 The data in the figure were collected during the third set of measurements, in the same mice.

993

994

995 Table 1. Body weights.

996 -----

997

Castrated

Intact

998 -----

999 3-month old

1000

Male

23.5±0.8^c

27.8±0.1

1001

Female

23.2±0.5

22.9±0.4

1002

1003 6-month-old

1004

Male

30.9±1.1

30.0±0.6

1005

Female

30.4±1.5^c

25.4±0.8

1006 -----

1007 c : significantly different from intact (p < 0.05).

1008 n=5-11/group

1009 The data in the Table 1 were collected during the first set of measurements.

1010

1011

1012 Table 2. Primers used.

1013 -----

1014 Name Sequence

1015 -----

1016 18S 5'-TCGTCTTCGAAACTCCGACT-3'

1017 5'-CGCGGTTCTATTTTGTGGT-3'

1018 ID1 5'-CTCGGAGTCTGAAGTCGGGA-3'

1019 5'-GAACACATGCCGCCTCGG-3'

1020 ALK3 5'-CTCTGAGAATTCTGAAGAAAGCAGC-3'

1021 5'-TCCTGCTGTCTCACTGGTGT-3'

1022 Smad4 5'-GAATAGCTCCAGCCATCAGTCT-3'

1023 5'-GAATGCACAATCGCCGGAGG-3'

1024 IGF 5'-AGCAGCCTTCCAACCTCAATTAT-3'

1025 5'-GAAGACGACATGATGTGTATCTTTATC-3'

1026 MuRF 5'-TGAGGTGCCTACTTGCTCCT-3'

1027 5'-GTGGACTTTTCCAGCTGCTC-3'

1028 MSTN 5'-GCTACCACGGAAACAATCAT-3'

1029 5'-CAATACTCTGCCAAATACCA-3'

1030 Atrogin 5'-TCACAGCTCACATCCCTGAG-3'

1031 5'-TCAGCCTCTGCATGATGTTC-3'

1032 FbxO30s 5'-AGGGACGTTTGTGGCAGTTT-3'

1033 5'-ACTGAATCGCCATACCTTCTC-3'

1034 -----

1035

1036

1037 Table 3. Contribution of male (MGRF) and female (FGRF) gonad-related factors to TA muscle
 1038 performance gains and growth (increased weight) between 1 month and 3 or 6 months of age.

1039 -----

1040	Sex	Age	Force	Power	Weight
1041	-----				
1042	Contribution of MGRF				
1043	Male	3 month	26%	58%	31%
1044	Male	6 month	29%	38%	0%
1045	Contribution of FGRF				
1046	Female	3 month	32%	0%	23%
1047	Female	6 month	20%	0%	12%
1048	-----				

1049 Force: absolute maximal force; Power: absolute maximal power. The contribution of
 1050 MGRF and FGRF to muscle performance gain was calculated as follow. For example,
 1051 absolute maximal force gain in castrated and intact 6-month old male mice was 142.2% and
 1052 101.3% respectively. Therefore, the contribution of MGF (%) to muscle P0 gain in 6-month
 1053 old male mice was $=100-(101.3/142.2)*100 = 28.8\%$.

1054 The data in the Table 3 were collected during the first set of measurements.

1055

1056

1057

1058

1059

Figure 1

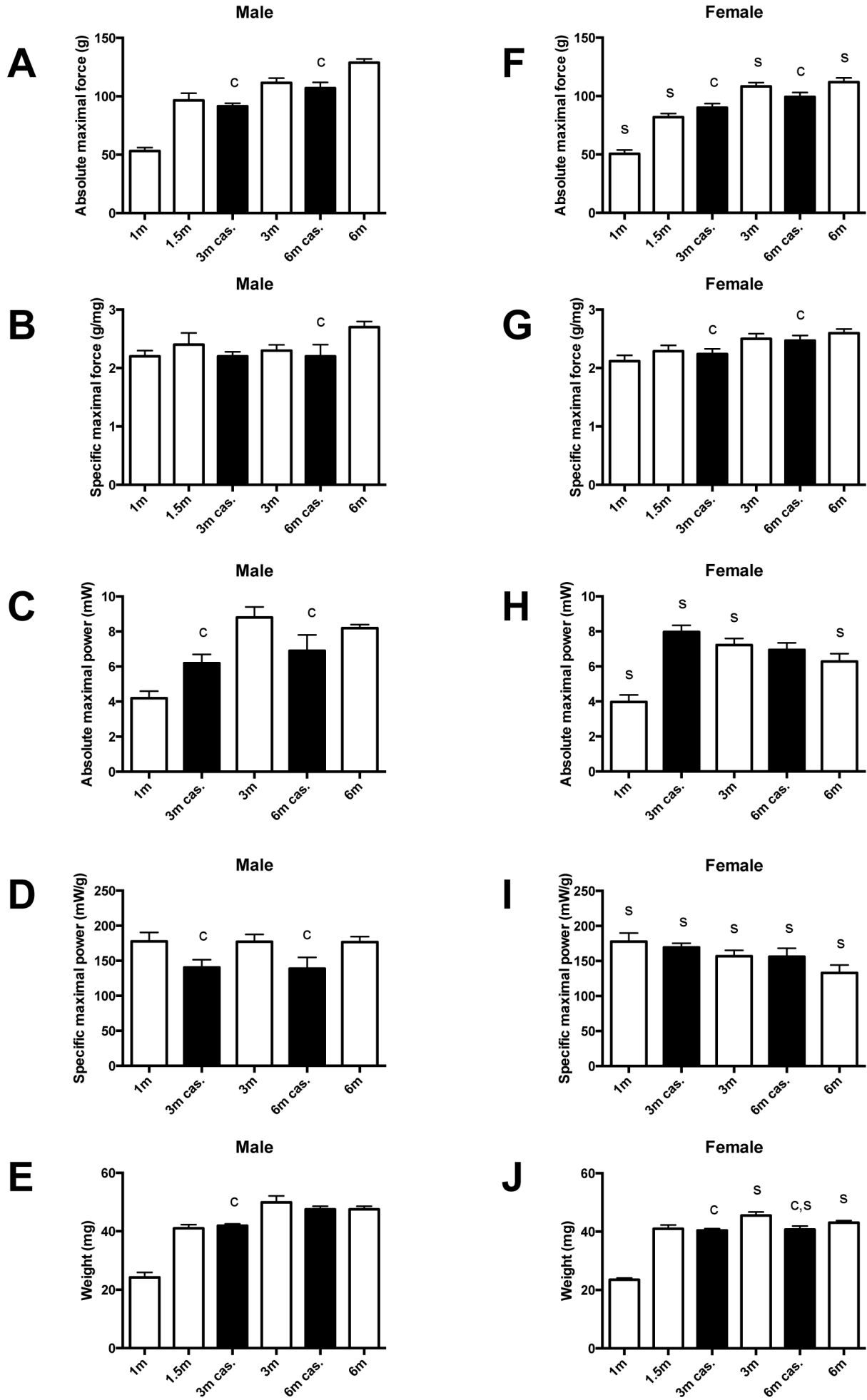


Figure 2

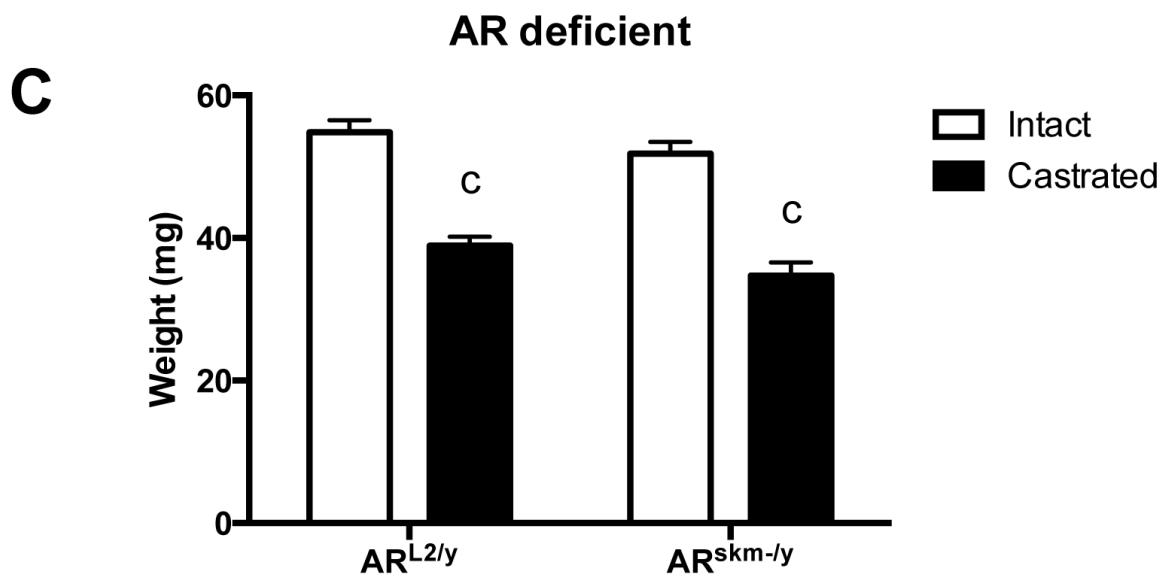
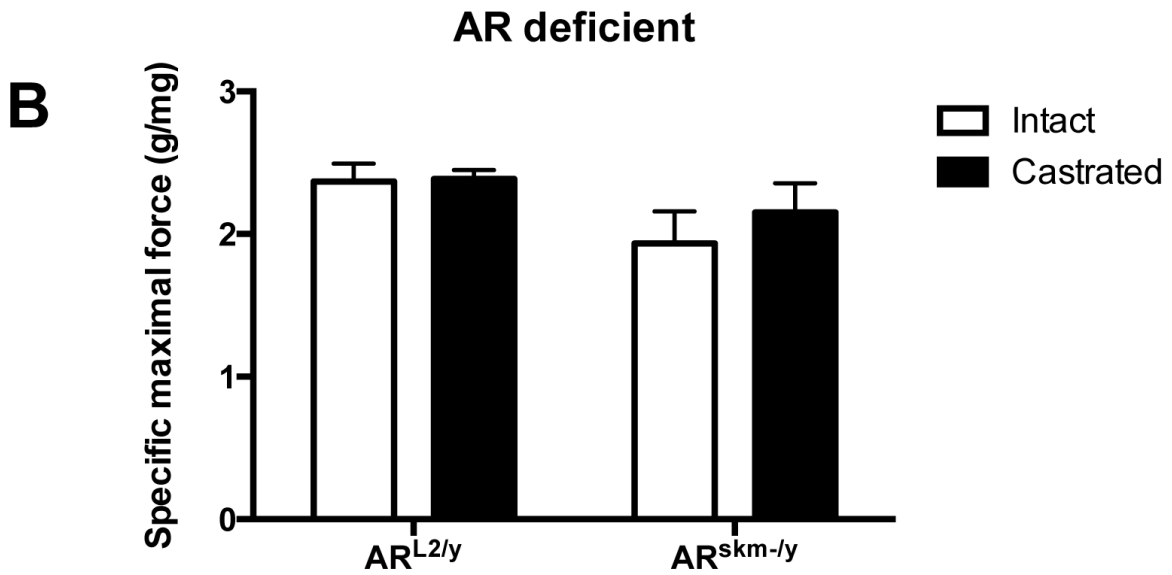
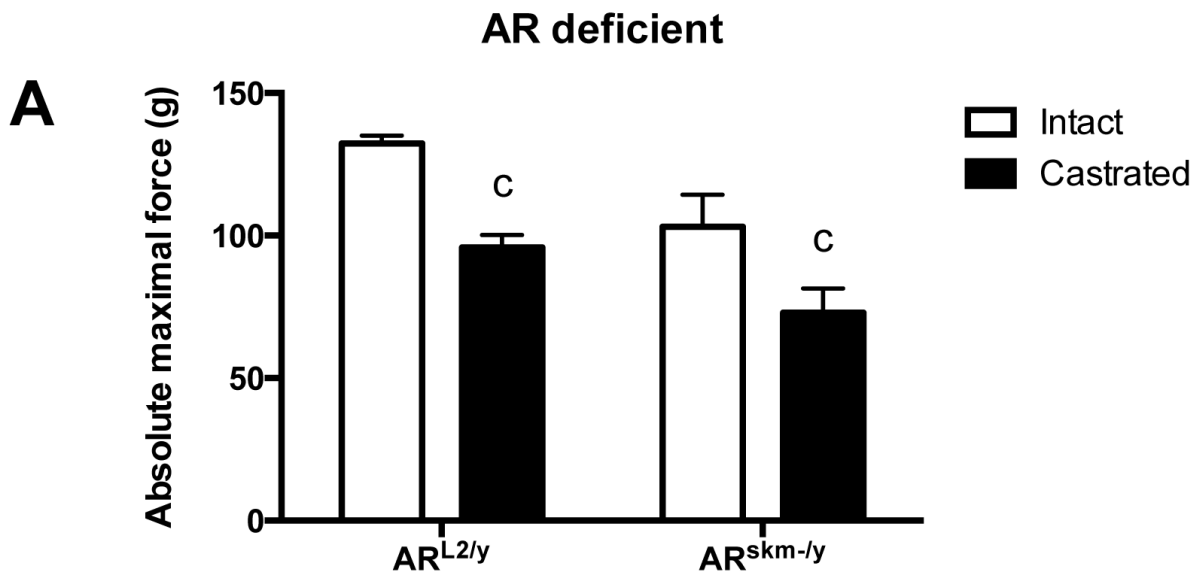
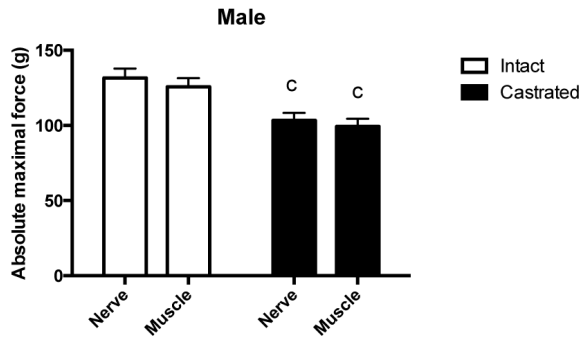
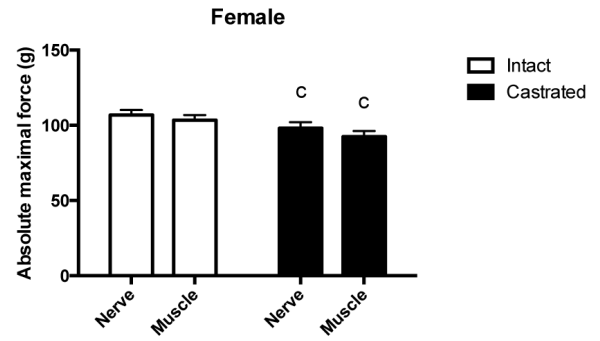


Figure 3

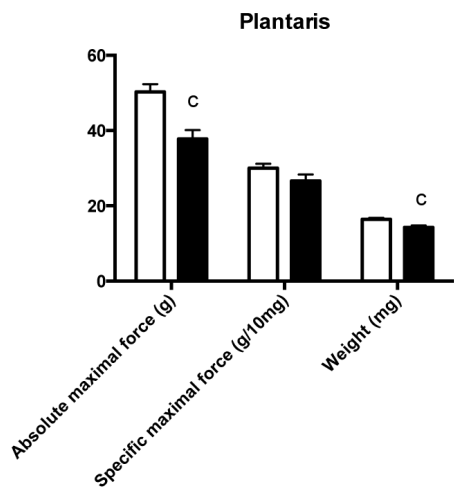
A



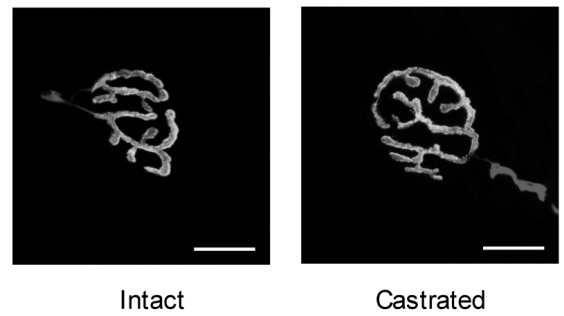
B



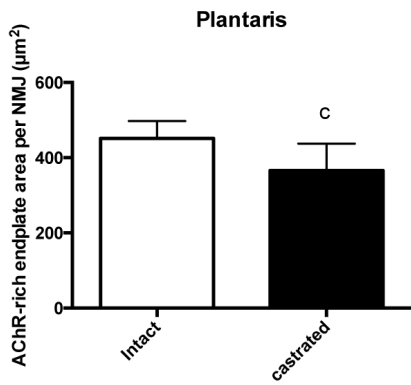
C



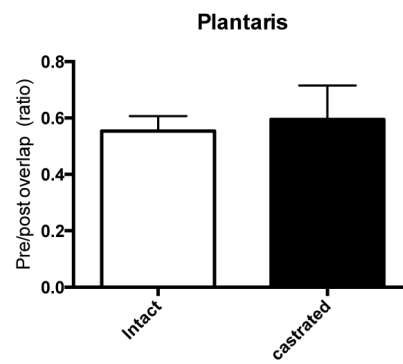
D



E



F



G

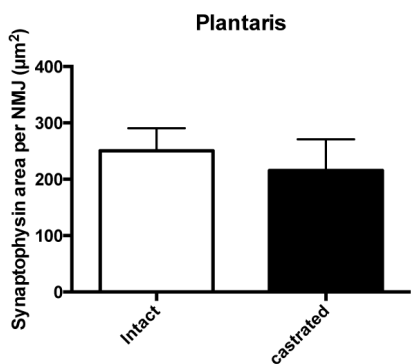


Figure 4

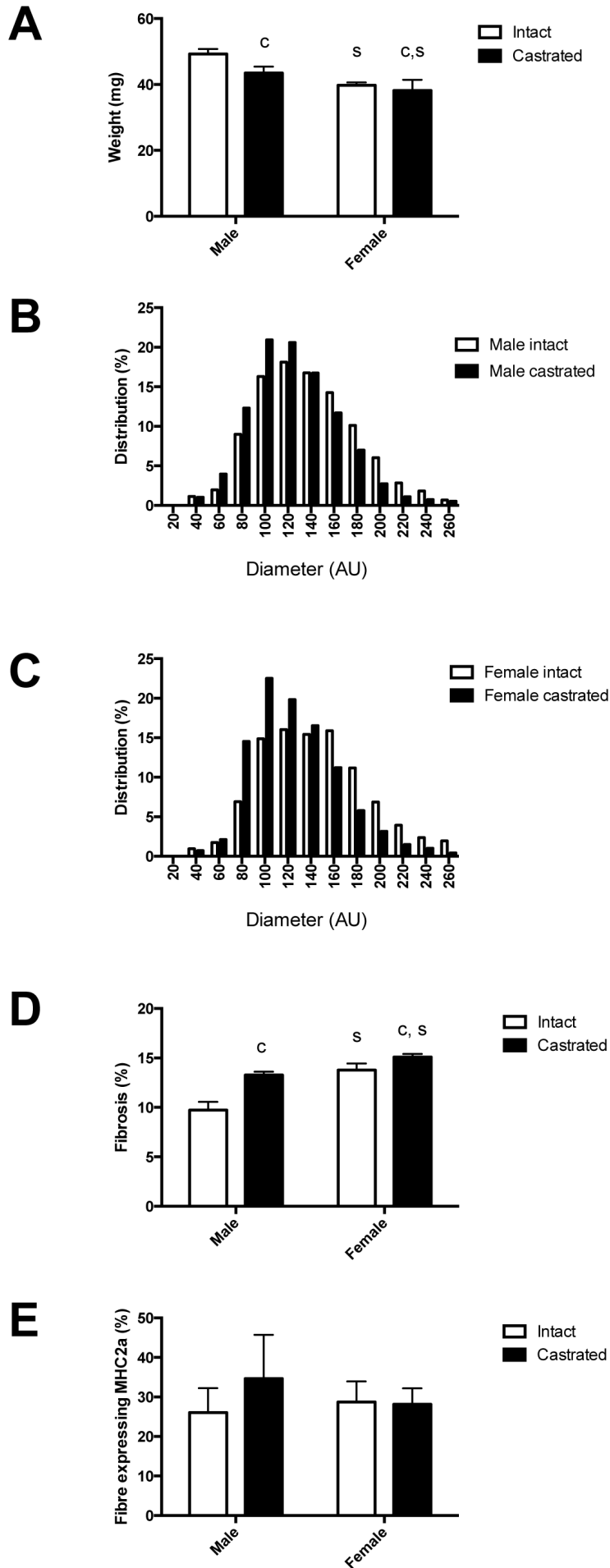
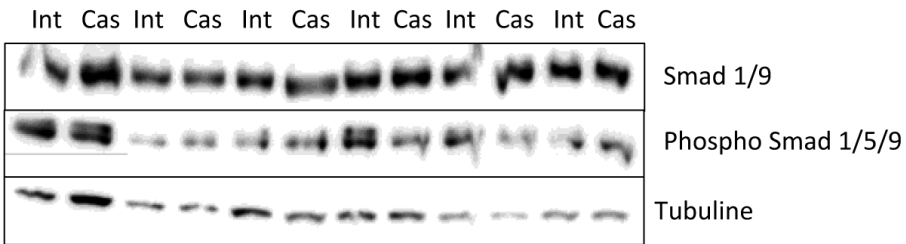
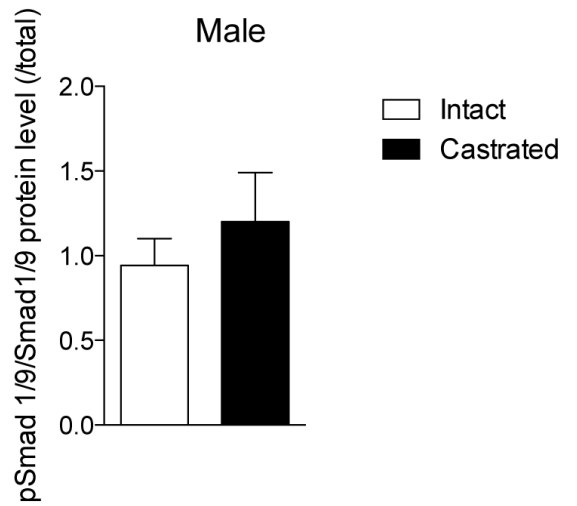


Figure 5

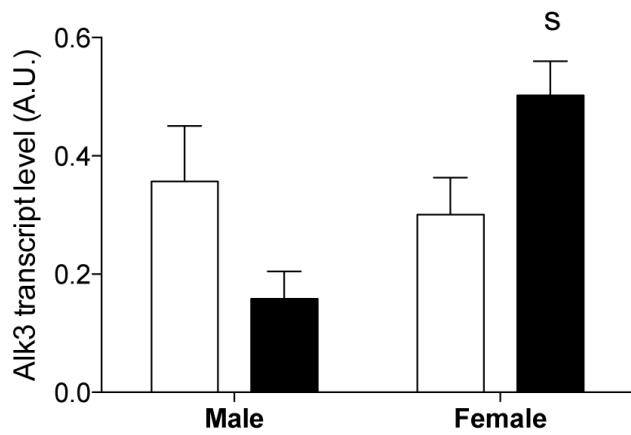
A



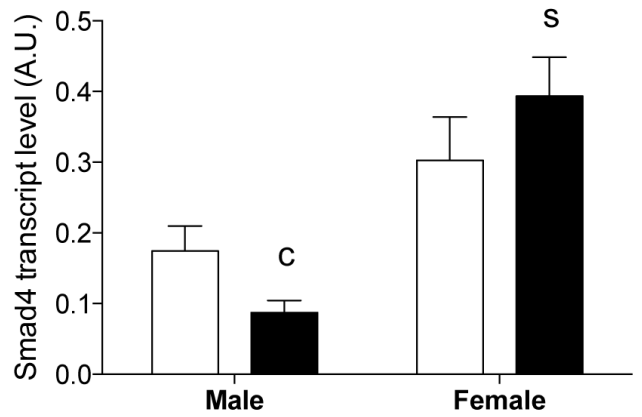
B



C



D



E

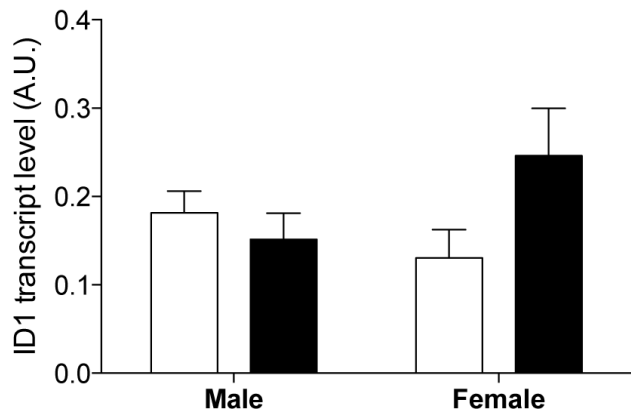
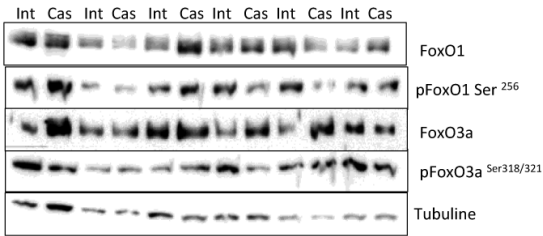
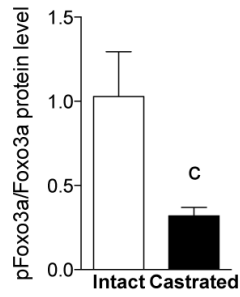


Figure 6

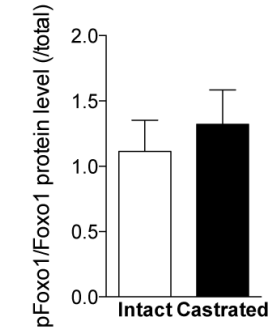
A



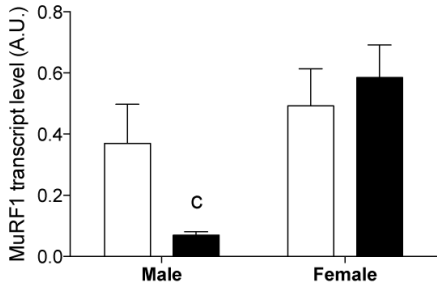
B



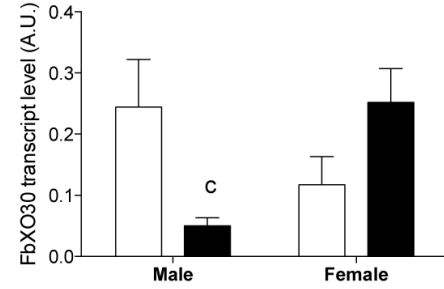
C



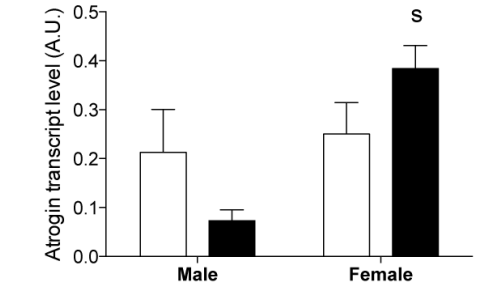
D



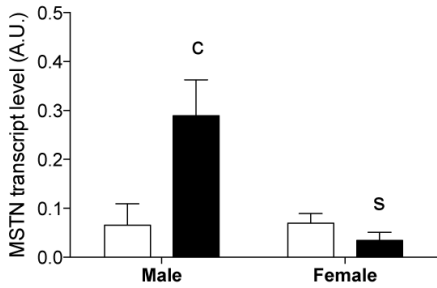
E



F



G



H

