

1 What is the impact of the rearing management applied during the heifers' whole life on the
2 toughness of five raw rib muscles in relation with carcass traits?

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16 Abstract

17 The aims of this study were, analysing the effects of rearing managements, carcass traits, and
18 muscle type (*M. complexus* [CP], *M. infraspinatus* [IF], *M. longissimus* [LM], *M.*
19 *rhomboideus* [RH], and *M. serratus ventralis* [SV]) on toughness of raw meat; developing
20 prediction models to act on their toughness. According to our results obtained on the data of
21 77 heifers, the IF raw muscle was the toughest and appeared the most sensitive to a change in
22 the rearing management. The four other raw muscles had a similar toughness within heifers

23 from the same rearing management. The five raw muscles were less tough when the carcass
24 was heavier and had higher dressing percentage and conformation. The 3 models explained
25 about 40% of the variability observed. Our models showed that it is possible to improve the
26 potential tenderness of raw meat, acting on: age of the heifer's mother, growth rate during the
27 growth and fattening periods, slaughter age, carcass weight and temperature 24h *post-mortem*.

28

29 **1 Introduction**

30 For consumers, the tenderness is the main expectation to purchase beef meat (Henchion et
31 al., 2014). However, this quality trait is highly variable according to many factors related to
32 (i) muscle properties (*e.g.* structural, metabolic, and contractile properties) (S.-H. Joo et al.,
33 2017; Listrat et al., 2020; Oury et al., 2010; Picard & Gagaoua, 2020; Totland & Kryvi, 1991;
34 Veiseth-Kent et al., 2018), (ii) animal type (*e.g.* breed, gender) (Bures & Barton, 2012;
35 Chambaz et al., 2003; Christensen et al., 2011; Gagaoua et al., 2016a), and (iii) technological
36 process (*e.g.* aging or cooking conditions) (Aviles et al., 2015; Gagaoua et al., 2016b).
37 Moreover, many studies showed that others factors as rearing managements (Couvreur et al.,
38 2019; Soulat et al., 2020) or carcass traits (Gagaoua et al., 2019; Soulat et al., 2020) had an
39 impact on the final tenderness of meat. Few works had studied the effect of these factors on
40 the toughness of raw meat, illustrating the tenderness potential of muscles (Christensen et al.,
41 2011; Ellies-Oury et al., 2012, 2017; Purchas & Zou, 2008). Furthermore, the studies of the
42 literature about the impact of rearing management on meat tenderness (on raw or cooked
43 meat) were mainly on *M. longissimus* (LM) considered as the reference muscle and concerned
44 mainly the fattening period. The toughness (raw meat) or the tenderness (cooked meat) of the
45 other muscles of the rib was weakly studied (Gruber et al., 2006; Soulat et al., 2019; Veiseth-
46 Kent et al., 2018). To our knowledge, no study of the literature analysed jointly the effects of
47 rearing managements and carcass traits on the toughness of several raw muscles of the rib.

48 However, when the consumers purchase and eat ribs or short ribs, several muscles with
49 different properties and levels of quality compose the wholesale cuts. Consequently, in the
50 present study we considered the main five muscles constituting the rib from the chuck sale
51 section. As the cooking conditions could be different according to countries or the consumer
52 tastes (rare, medium-rare or well-cooked) and had an impact on the final tenderness of meat
53 (Gagaoua et al., 2016b), we chose to evaluate the toughness of aged meat on raw muscles to
54 be in conditions as close as possible to those of the consumer when he buys the meat.
55 Moreover, we considered the rearing management applied during the heifers' whole life and
56 not only during the fattening period as in Soulat et al. (2020). So, the first aim of this work
57 was to analyse the effect of rearing managements, carcass quality, and their interaction on the
58 toughness measured by Warner-Bratzler shear force, of five raw rib muscles: M. *complexus*
59 (CP), M. *infraspinatus* (IF), LM, M. *rhomboideus* (RH), and M. *serratus ventralis* (SV). The
60 second aim was to identify rearing factors and/or carcass traits that could be used to manage
61 simultaneously the toughness of these five raw muscles.

62 **2 Material and methods**

63 *2.1 Animals, rearing managements, slaughtering and carcass traits*

64 This study used 77 crossed Charolais x Aubrac heifers from eight commercial farms.
65 Surveys were performed to collect 46 rearing factors (Tables 1 to 3) characterizing three key
66 periods of the whole heifers' life (from birth to slaughter): pre-weaning (PWP), growth period
67 (GP) and fattening period (FP) (Soulat et al., 2018a). Then, the four rearing managements
68 (RM) described by Soulat et al. (2020) were used in this study. The main characteristics of
69 these RM are summarized in the Fig. 1.

70 The 77 heifers were slaughtered in the same industrial slaughterhouse (Abattoir du
71 Gévaudan, Antrenas, France). Six carcass traits were collected: cold carcass weight

72 (calculated from the measured hot carcass weight x 0.98, kg), dressing percentage (ratio of
73 cold carcass weight to live weight before slaughter, %), conformation and fat scores using the
74 EUROP system (EC, 2006) and the pH and the temperature at 24 h *post-mortem* (pH 24h and
75 Temp 24h, respectively) (Table 4). In the EUROP system, the conformation score is divided
76 into five ordered classes (E = very high; to P = very poor muscle development). Moreover,
77 each class has three subdivisions (high: “+”, average: “=”, and low: “-”). The fat score is
78 divided into five ordered classes (1 = lean; to 5 = very fat). All carcasses of this study had a
79 fat score of 3, consequently this parameter was not considered.

80 The two carcass quality clusters (CARCA-Low and CARCA-High) described by Soulat et
81 al. (2020) were used in this study. The carcasses in CARCA-High had significantly higher
82 cold weight, and dressing percentage than those in CARCA-Low. Moreover, the CARCA-
83 High cluster was composed mainly by carcasses of the classes U+ and U=, whereas the
84 CARCA-Low cluster was composed by carcasses of the classes U- and R+.

85 *2.2 Muscle sampling and meat quality trait*

86 Two beef ribs (the 5th and the 4th) of each carcass were collected, at 24 h *post-mortem*, as
87 described in Soulat et al. (2020). Then, each beef rib sample (n = 77) was individually
88 vacuum-packaged and aged for 14 days at 4 °C. After, these samples were frozen and stored
89 at -20 °C until the analyses.

90 After thawing of the beef rib samples (around 48h), the shear force was measured on five
91 muscles: CP, IF, LM, RH, and SV, using a Warner-Braztler apparatus (EZ-SX set assay EU
92 RoHS, Shimadzu, Kyoto, Japan). For each beef rib samples, the five muscles were dissected
93 and meat portions (length: 1.5 to 3 cm; width: 1 cm; and thickness: 0.5 to 1 cm) were cut. The
94 shear force was measured cutting perpendicularly to the fibers of the raw meat portions (least

95 five portions) obtained and calculated using the Trapezium X 1-5.1 software (Shimadzu,
96 Kyoto, Japan) (Wheeler et al., 1997).

97 For each muscle, the data of shear force are presented in the Table 4.

98 *2.3 Statistical analyses*

99 Statistical analyses were performed using R 4.0.0 software (R core Team, 2020). The
100 statistical procedures performed in this work were summarized in the Fig. 2.

101 *2.3.1 Descriptive statistical analyses*

102 For the shear force, an ANOVA with random effects (mixed model) was performed to
103 evaluate its dependence on the RM, the carcass quality cluster and the muscle. The fixed
104 effects were: RM, carcass quality, muscle, RM x muscle interaction, and carcass quality x
105 muscle interaction; and the random effect was: animal. If an interaction was not significant in
106 the ANOVA, a new ANOVA was performed without this interaction in the model. Then, if
107 the results of the mixed model were significant, a Tukey test was performed. The mixed
108 model was performed using the “lmerTest” (Kuznetsova et al., 2017) package and the Tukey
109 test was carried out using the “emmeans” (Lenth, 2020) and “multcompView” (Graves et al.,
110 2019) packages.

111 A principal component analysis (PCA) was performed to illustrate the relationships
112 between the shear force values of the 5 muscles, using the “FactoMineR” (Le et al., 2008)
113 package.

114 *2.3.1 Predictive statistical analyses*

115 Before establishing the models of prediction, a first step was performed to test the
116 multicollinearity between the 46 rearing factors (Fig. 2). The multicollinearity was tested
117 using the variance inflation factors (VIF) calculated from the “car” package (Fox & Weisberg,

118 2019). As explained by Soulat et al. (2018a), the explicative variables with the greatest VIF
119 were removed one by one, to finally obtain explicative variables with $VIF < 10$.

120 After this step, 19 rearing factors were retained (these rearing factors are described in
121 Tables 1 to 3, in bold):

122 - Rearing factors for the pre-weaning period ($p = 10$):

- 123 • Birth weight
- 124 • Age of the heifer's mother at the heifer's birth (age of the cow)
- 125 • Age of the heifer's mother at first calving
- 126 • Pre-weaning duration
- 127 • Total time spent by the calf with her mother between the birth and the
128 weaning
- 129 • Insemination type (artificial or natural)
- 130 • Calving (intervention or not of the farmer during the calving)
- 131 • Calculated average of the concentrates' crude protein in the diet during PWP
- 132 • Average daily gain (ADG) of the calf between the birth and the weaning
- 133 • Offered or not concentrates in housing calf diet during PWP

134 - Rearing factors for the growth period ($p = 2$):

- 135 • ADG between the weaning and the beginning of the fattening period
- 136 • Nature of pasture (during the pasture, heifers diet was complemented by hay
137 or not).

138 - Rearing factors for the fattening period ($p = 7$):

- 139 • Slaughter age
- 140 • ADG between the beginning of FP and the slaughter

- 141 • Calculation of the grass silage percentage in the average diet across the whole
- 142 FP
- 143 • Calculation of the wrapped haylage percentage in the average diet across the
- 144 whole FP
- 145 • Calculated average of the forage's crude protein content across the whole FP
- 146 • Calculated average of the forage's net energy content across the whole FP
- 147 • Calculated average of the concentrate's net energy content the whole FP

148 This process was similarly performed on the carcass traits ($p = 5$) which all had VIF < 10.

149 Three linear models were developed to predict the shear force (SF) of the 5 muscles. The
150 first one (RF_SF) was obtained from the selected rearing factors, the second one
151 (CARCA_SF) from the carcass data, and the last one (RF&CARCA_SF) from the selected
152 rearing factors and the carcass data (Fig. 2).

153 To obtain our final prediction models, the procedure described in Soulat et al. (2018a) was
154 applied. For example, initially in the complete RF_SF model, all rearing factors selected and
155 the muscle factor were included. Then, the non-significant rearing factors were removed one
156 by one to obtain the simplest prediction model. After each withdrawal, using a probability
157 ratio test, the new model was compared with the previous model. If the result of the
158 comparison between 2 models was $P < 0.10$, the independent variable was conserved (Fig. 2).

159 As an external validation of the prediction models was not possible with the number of
160 animals in our dataset, the validation of each model was performed using the bootstrap
161 procedure (Tan et al., 2006). For each developed model, this procedure was repeated 500
162 times to generate 500 bootstrap samples. After the bootstrap procedure, the mean coefficient
163 of each independent variable was calculated. The number of times the coefficients of the
164 independent variables in the model were significant was counted over the 500 repetitions.

165 To evaluate the quality of the prediction models, three criteria were considered to describe
166 the robustness of the model from the root mean square errors of prediction (RMSEP,
167 (Kobayashi & Salam, 2000)), the accuracy of the model from the mean prediction error
168 (MPE, (Yan et al., 2007)), and the precision of the model from the coefficient of
169 determination (R^2). In this study, the RMSEP, MPE, and R^2 were calculated at each repetition
170 of the bootstrap. Then, the mean of these three criteria was calculated. As in Bonnet et al.
171 (2020), the developed models were considered to have a high or good accuracy when MPE
172 ranged from 0.10 to 0.30 and to have a high precision when R^2 was the closest to 1. To
173 compare the different prediction models, the Akaike information criterion (AIC) was also
174 calculated. The best model has the lowest calculated AIC, RMSEP, and MPE values and the
175 highest R^2 value.

176 **3 Results and discussion**

177 *3.1. Effects of the rearing managements, muscle, and carcass quality clusters on the* 178 *toughness of raw aged meat*

179 According to our results, the interaction between the rearing management and muscle, and
180 the carcass clusters had a significant effect on the toughness of the raw meat (Table 5). The
181 toughness of the CP, LM, RH, and SV muscles was not significantly different when the
182 heifers received the same rearing management (Fig. 3). In cattle, the RH and SV muscles are
183 postural muscles, the LM is a support muscle, and the CP muscle is involved in the movement
184 of the animal's head (Totland & Kryvi, 1991; University of Nebraska-Lincoln, 2020). The
185 muscle fiber characteristics could be impacted by the muscle type (S. T. Joo et al., 2013;
186 Picard & Gagaoua, 2020; Totland & Kryvi, 1991). However, the location and the function of
187 these 5 muscles did not seem to have an impact on their toughness. The toughness of IF
188 muscle, which is also a postural muscle, was the highest among the 5 muscles and the most
189 sensitive to changes in rearing managements. More precisely, the IF muscle was tougher for

190 heifers from RM-4 than for those from RM-2 and RM-3 (Fig. 3). According to the traits of the
191 4 rearing managements described in Soulat et al. (2020) and used in this work, the main
192 differences between RM-4 and both rearing managements 2 and 3 were:

- 193 - During PWP, the calves from RM-4 had higher average daily gain and pasture
194 duration than those from RM-2 and RM-3
- 195 - During GP, the heifers from RM-4 had lower number of days of offered concentrates
196 in the diet and lower pasture duration than those from RM-2 and RM-3. The average
197 concentrate's crude protein and net energy contents (calculated across the whole
198 growth period) were lower in RM-4 than in RM-2 and RM-3.
- 199 - During FP, the fattening of heifers from RM-4 was performed at pasture. In this
200 rearing management, the heifers were older at the beginning of their fattening than
201 those from RM-2 and RM-3. The heifers from RM-4 had lower concentrate intake
202 during this period than those from RM-2 and RM-3. The average forage's crude
203 protein and neutral detergent fiber contents (calculated across the whole fattening
204 period) were lower in RM-4 than in RM-2 and RM-3.

205 In the literature, there are few works which studied the effects of several rearing factors on
206 the toughness of raw meat. Moreover, there are also few works which studied the effects of
207 rearing factors applied before the fattening period on the meat tenderness. These results were
208 obtained on cooked meat making it difficult to compare to ours results.

209 Hennessy et al. (2001) observed that the tenderness of LM was lower when calves had a
210 quick growth before weaning. In our study, the calves from the RM-4 had a quicker growth
211 before weaning than those from RM-2 and RM-3. However, the toughness of raw LM was
212 similar for these 3 rearing managements (Fig. 3). In our study, the animals were slaughtered
213 older than those in Hennessy et al. (2001). No significant differences were observed between
214 these 3 rearing managements for the other muscles except for the raw IF muscle. It was

215 possible that the slaughter age mitigated the effect of the growth rate before weaning, except
216 on the toughness of IF. Modzelewska-Kapitula & Nogalski (2016) showed that the proportion
217 of fat in the raw IF muscle was significantly higher when the young bulls had a quick growth
218 during their fattening. The growth speed of animal could had an impact more or less
219 important according to the muscle.

220 During the growth period, Miller et al. (1987) did not observe an effect of the diet's
221 energetic level on the tenderness of LM, M. semimembranosus, and M. semitendinosus
222 cooked meat. It could be possible that the IF muscle was more sensitive to this factor than
223 these three muscles.

224 During the fattening period, the heifers consumed variable concentrate quantities according
225 to the rearing management. However, many studies did not observe an effect of the
226 concentrate quantity in the fattening diet on the tenderness of LM after cooking (French et al.,
227 2001; Keady et al., 2013; Moloney & Drennan, 2013). Moreover, during their life, the heifers
228 from the RM-4 had the longest pasture duration, consequently these heifers had a higher
229 physical activity than those in housing. According to the results of Cozzi et al. (2010), the LM
230 after cooking was tougher when heifers performed their fattening at pasture. This result could
231 partly explain why the raw IF muscle is tougher for heifers from the RM-4. The physical
232 activity could have an effect on the connective tissue and/or the myofibril integrity of this
233 muscle. The results of Modzelewska-Kapitula & Nogalski (2016) showed that the fattening
234 diet had not a significant effect on the tenderness of IF muscle after cooking, in young bulls
235 fattening in a free-stall. However, for the LM, Pordomingo et al. (2012) did not observe an
236 effect of the fattening type (pasture vs. housing) on the meat tenderness, in heifers.

237 In accordance with previous results, the difference of IF toughness observed between the
238 rearing managements could not be explained by one rearing factor (Soulat et al., 2020;
239 2018b).

240 Moreover, the raw IF muscle was also tougher than the four other muscles regardless of the
241 rearing management (Fig. 3). After 24h *post-mortem*, Torrescano et al. (2003) observed also
242 that the raw IF muscle was tougher than the raw LM. The IF muscle is an oxidative muscle
243 and contained a higher proportion of type I fibers (79%) and a lower proportion of type IIA
244 and IIX fibers than LM, SV, and RH (Totland & Kryvi, 1991). The IF muscle is one of the
245 major postural muscles in the forepart with mean size of type I above 4000 μm^2 and IIX
246 between 2000 and 2500 μm^2 , respectively (Totland & Kryvi, 1991). The mean size of type I
247 fibers of SV muscle was also above 4000 μm^2 , whereas, the mean size of type IIX fibers was
248 between 3000 and 3500 μm^2 . For the LM, the size of type I and IIX fibres was below 3100
249 μm^2 and above 3800 μm^2 (Jurie et al., 2005, 2007). According to the results of Torrescano et
250 al. (2003), the IF muscle had more insoluble collagen than the raw LM, without aging. After
251 aging, the IF muscle had lower myofibrillar fragmentation index, higher sarcomere length,
252 proportion of intramuscular fat, collagen level, and pH 48h than LM (Purchas & Zou, 2008;
253 Veiseth-Kent et al., 2018). These different traits between the IF and the others rib's muscles
254 could explain the difference of toughness observed for the raw meat.

255 The result of the PCA showed that the tenderness of IF muscle was less correlated with the
256 tenderness of the other four muscles (Fig. 4). However, the shear force values of the 5
257 muscles were positively correlated.

258 Only for heifers from RM-2, the LM was more tender than CP and RH muscles, without
259 cooking (Fig. 3). The main differences of the RM-2 with the 3 other were during the fattening
260 period (Fig. 1). Briefly, the heifers from RM-2 were lighter and younger at the beginning of
261 the fattening with a fattening outside without pasture. Moreover, the fattening duration was
262 the longest and the quantity of concentrate intake was the highest. In accordance with our
263 results, Thenard et al. (2006) observed also that the raw RH muscle was tougher than the LM.
264 According to these authors, the RH muscle had higher total collagen and lower proportion of

265 soluble collagen than LM. The RH contained a higher proportion of type I fibers and a lower
266 proportion of type IIA fibers than LM (Totland & Kryvi, 1991). The toughness difference
267 observed between both muscles could be mainly explained by the muscle traits. To our
268 knowledge, there are no works studying the toughness of raw CP. However, the RH was
269 tougher than CP after cooking (Bratcher et al., 2005).

270 The five raw muscles were the tougher for CARCA-Low cluster (Table 5). According to
271 Soulat et al. (2020) and Gagaoua et al. (2019), the carcass traits can be linked to a higher
272 overall tenderness. The heavier carcasses with higher dressing percentage and conformation
273 produced raw LM and M. *rectus abdominis* (RA) more tender, in heifers (Ellies-Oury et al.,
274 2017; Soulat et al., 2020). For cooked meat, Gagaoua et al. (2019) observed that the LM had
275 the highest tenderness when the carcasses had a fat score ≥ 2.42 , a cold carcass weight < 419
276 kg, and a dressing percentage $\geq 60\%$. However, Couvreur et al. (2019) did not observe
277 difference on the tenderness of LM in cull cows between both clusters: Ylight (young and
278 light cows) and Yheavy (young and heavy cows), after cooking. Moreover, after 14 days of
279 aging, Ellies-Oury et al. (2017) and Agbeniga & Webb (2018) did not observe an effect of
280 cold carcass weight on the tenderness of RA and LM muscles, respectively.

281 *3.2. Identification of rearing factors and carcass traits to reduce the toughness of the five raw* 282 *aged rib's muscles*

283 In this work, three models were proposed to predict the shear force of the five-aged rib's
284 muscles. In the RF_SF and CARCA_SF models, the shear force was only predicted from
285 rearing factors or carcass traits, respectively. In the RF&CARCA_SF, the shear force was
286 predicted from rearing factors and carcass traits. The parameters of prediction quality (AIC,
287 R^2 and MPE) of these three models were similar (Table 6). However, these models explained
288 only about 40% of the shear force's variability observed.

289 According to the coefficient of the independent variables in the 3 models, if one of these
290 variables was increased, the raw meat was low tough.

291 In the RF_SF model, the independent variables considered were age of the cow, the ADG
292 during GP and FP, and the slaughter age (Table 6).

293 To our knowledge, the effect of the age of the cow on the meat toughness has not been
294 studied. It is possible that the physiological stage, the genetic and/or the epigenetic of the cow
295 influence the meat toughness of this progeny.

296 Contrary to our results, Hennessy et al. (2001) observed a decreased of LM tenderness
297 when the calves had high ADG before weaning. In our study, heifers were slaughtered older
298 than cattle in Hennessy et al. (2001). Although the slaughter age was less often significant in
299 the RF_SF model compared to the three others independent variables, this rearing factors had
300 an impact on the toughness. In accordance with Soulat et al. (2018a) for the RA, the slaughter
301 of older heifers allowed to have a tenderness meat higher. Ahnstrom et al. (2012) and Bures &
302 Barton (2012) observed also an increase of the LM tenderness when the heifers were
303 slaughtered older.

304 The raw meat from these five muscles is potentially less tough if the heifer's mother is an
305 older cow, if the heifer has a quick growth during GP and FP, and/or if the heifer is
306 slaughtered older.

307 In the CARCA_SF model, the independent variables considered in the model were the cold
308 weight and Temp 24h of the carcass (Table 6). In accordance with our results, Ellies-Oury et
309 al. (2017) observed that the raw RA was more tender when the carcasses were heavier, in
310 heifers. After cooking, these authors did not observe an effect of carcass weight on the
311 tenderness of RA muscle. According to the results of Agbeniga & Webb (2018), the LM from
312 heavy carcasses was also more tender than those from light carcasses after 3 days of aging

313 and cooking. However, no effect of the carcass weight was observed on the LM tenderness
314 after 14 days of aging, by these authors. Moreover, some studies observed that the LM was
315 significantly more tender when the young bulls or steers were slaughter heavier (Keane &
316 Allen, 1998; Sañudo et al., 2004). In our model CARCA_SF, Temp 24h of the carcass had an
317 effect on the toughness of the raw meat. According to our results, the carcasses with a slow
318 chilling produce a raw meat low tough. This result reinforces that the shear force of LM
319 increased with a quick chilling of the carcass (Mao et al., 2012; Zhang et al., 2019).

320 Our results displayed that the heavier carcasses with a Temp 24h higher increased the
321 potential to obtain raw meat low tough, independently of the rearing management.

322 When both rearing factors and carcass traits are considered simultaneously in the
323 RF&CARCA_SF model, the independent variables included in the model were age of the cow
324 and the cold weight and the temperature at 24h of the carcass (Table 6). In this model, we
325 found independent variables considered in RF_SF and CARCA_SF. However, the
326 simultaneous consideration of the rearing factors and the carcass traits did not allow to an
327 improvement in the prediction quality of the five muscles' shear force.

328 For the same prediction quality of the shear force, the CARCA_SF model seems to be the
329 simplest model to implement because its independent variables are easily recoverable at the
330 slaughterhouse. However, the RM_SF appeared also interesting to manage the tenderness
331 potential of raw meat early.

332 **4. Conclusion**

333 These results showed that the 4 rearing managements applied during the heifers' whole life
334 did not significantly impact the toughness of the raw CP, LM, RH, and SV muscles. They
335 displayed that the toughness of the raw IF muscle was higher and more sensitive to the rearing

336 management than the other muscles. Moreover, the toughness of the five muscles was lower
337 when the carcass was heavier and had higher dressing percentage and conformation score.

338 Our results displayed also some rearing factors (age of the cow, ADG during GP and FP,
339 and slaughter age) and some carcass traits (cold carcass weight and Temp 24h) which could
340 be used as lever to improve the potential tenderness of the 5 raw rib's muscles studied.

341 Consequently, these data highlighted that it could be possible to manage simultaneously the
342 tenderness potential of different rib's muscles during the animals' life. **This work can**
343 **contribute to study the potential tenderness of meat to help the beef sector (from the farm to**
344 **the plate of consumer) to improve the quality of meat products by adaptation of the rearing**
345 **system.**

346 In complement to this work, it would be interesting to study the effects of the rearing
347 managements and carcass traits on the tenderness of cooked meat to precise the effect of
348 cooking on the potential tenderness, and to analyse others muscles from the same carcass to
349 evaluate the quality of many meat cuts.

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520

521 **List of figures**

522

523 **Fig. 1.** Summary of the four rearing managements applied during the heifers' whole life
524 defined by Soulat et al. (2020) (ADG = average daily gain; Tot_duration_CC = total time
525 spent by the calf with her mother between the birth and the weaning; Conc_duration =
526 number of days of offered concentrates in the diet; Conc_quant_intake = average daily
527 quantity intake per heifer, Conc_NE = calculated average of concentrate's net energy content;
528 Conc_CP = calculated average of concentrate's crude protein content; Forage_CP = calculated
529 average of the forage's crude protein content; Forage_NDF = calculated average of the
530 forage's neutral detergent fiber content).

531

532 **Fig. 2.** Framework of the statistical procedures performed in this study: descriptive and
533 predictive analyses. (RF: rearing factor, CARCA: carcass, SF: shear force)

534

535 **Fig. 3.** Effect of the interaction between the rearing managements (RM) and the muscles (M.
536 *complexus*, CP; M. *infraspinatus*, IF; M. *longissimus*, LM; M. *rhomboideus*, RH; and M.
537 *serratus ventralis*, SV) on the shear force of raw meat. ^{a,b,c,d,e,f}Estimated marginal means
538 (emmeans) in different letters were significantly different ($P < 0.05$).

539

540 **Fig. 4.** Principal component analysis of shear force of the raw five rib's muscles (M.
541 *complexus*, CP; M. *infraspinatus*, IF; M. *longissimus*, LM; M. *rhomboideus*, RH; and M.
542 *serratus ventralis*, SV).

543

544 **Table 1**

545 Description of the rearing factors characterizing the pre-weaning period (PWP) (in bold, the rearing factors conserved after the test of
 546 multicollinearity).

Pre-weaning period					
Quantitative rearing factors	Description of the rearing factor		Mean \pm SE ¹	Min	Max
Age of the cow (year)	Age of the heifer's mother at the heifer's birth		6.9 \pm 0.3	2.6	14.0
Age at the first calving (month)	Age of the heifer's mother at first calving		34.4 \pm 0.3	26.0	38.0
Birth weight (kg)	Calf weight at birth		41 \pm 0.5	28	53.0
ADG_PWP (kg/day)	Average daily gain of the calf between the birth and the weaning		1.0 \pm 0.02	0.6	1.3
Duration_day_CC (hour/day)	Time spent per day by the calf with her mother during the housing period		12.1 \pm 1.3	0.3	24.0
Tot_duration_CC (day)	Total time spent by the calf with her mother between the birth and the weaning		194.0 \pm 7.9	110.9	305.0
Conc_duration_PWP (day)	Number of days of offered concentrates in the diet during PWP		83.8 \pm 7.2	0.0	236.0
Conc_CP_PWP (g/kg DM ²)	Calculated average of the concentrates' crude protein in the diet during PWP		98.7 \pm 6.5	0.0	264.3
Conc_NE_PWP (day)	Calculated average of the concentrates' net energy in the diet during PWP		0.8 \pm 0.1	0.0	1.8
Pasture_duration_PWP (day)	Numbers of days spend at pasture during PWP		143.2 \pm 2.8	107.0	174.0
PWP_duration (day)	Number of days between the birth and the weaning of the calf		254.7 \pm 3.7	156.0	306.0
Qualitative rearing factors	Modalities of the rearing factors	Description of the rearing factor	n		
Insemination type	Artificial	Artificial insemination using frozen semen	37		
	Natural	Insemination performed by a bull	40		
Calving	Easy	Natural calving	61		
	Help	Farmer intervention during the calving	16		
Bull type	Bull-3y	3-year-old bulls belonging to the farmer	25		
	Bull->3	Bull older than 3 years belonging to the farmer	23		
	Bull-IA-CE	Artificial insemination from frozen semen for calving ease	9		
	Bull-IA-EM	Artificial insemination from frozen semen for early maturity	8		
	Bull-IA-CE&EM	Artificial insemination from frozen semen for calving ease and early maturity	12		
Conc_housing_PWP	Yes	Offered concentrates in housing calve diet during PWP	66		
	No	No offered concentrates in housing calve diet during PWP	11		
Conc_pasture_PWP (%)					

	Yes	Offered concentrates in pasture calve diet during PWP	17
	No	No offered concentrates in pasture calve diet during PWP	60
547			
548	¹ SE = standard error.		
549	² DM = dry matter.		
550			
551			
552			
553			

554 **Table 2**

555 Description of the rearing factors characterizing the growth period (GP) (in bold, the rearing factors conserved after the test of multicollinearity).

Growth period					
Quantitative rearing factors	Description of the rearing factor		Mean \pm SE ¹	Min	Max
Age at the weaning (month)	Age of heifer at the weaning		8.5 \pm 0.1	5.2	10.1
Weaning weight (kg)	Heifer weight at the weaning		291 \pm 12.7	168	374
ADG_GP (kg/day)	Average daily gain of the heifer between the weaning and the beginning of the fattening period		0.6 \pm 0.01	0.3	0.8
Conc_quant_intake_GP (kg)	Total concentrate quantity intake per heifer during the GP		290.9 \pm 27.7	45.9	845.5
Conc_duration_GP (day)	Number of days of offered concentrates in the diet during GP		207.5 \pm 13.5	51.0	407.0
Conc_CP_GP (g/kg DM ²)	Calculated average of concentrate's crude protein content across the whole GP		98.35 \pm 6.7	12.62	187.6
Conc_NE_GP (Mcal/kg DM)	Calculated average of concentrate's net energy content across the whole GP		0.9 \pm 0.1	0.2	1.9
Pasture_duration_GP (day)	Number of days spend at pasture during GP		275.1 \pm 6.2	197.0	349.0
Qualitative rearing factors	Modalities of the rearing factors	Description of the rearing factor	n		
Hay_GP (%)	< 20%	Across the whole GP, the calculated average percentage of hay in the housing diet was below 20%	10		
	[20%; 40%[Across the whole GP, the calculated average percentage of hay in the housing diet was between 20% and 40% not included	31		
	[40%; 80%]	Across the whole GP, the calculated average percentage of hay in the housing diet was between 40% and 80%	19		
	> 80%	Across the whole GP, the calculated average percentage of hay in the housing diet was above 80%	17		
Grass_silage_GP (%)	0%	Across the whole GP, the heifers had not grass silage in the housing diet	42		
	< 50%	Across the whole GP, the calculated average percentage of grass silage in the housing diet was below 50%	8		
	> 50%	Across the whole GP, the calculated average percentage of grass silage in the housing diet was above 50%	27		
Wrapped_haylage_GP (%)	0%	Across the GP, the heifers had not wrapped haylage in the housing diet	41		
	< 40%	Across the GP, the calculated average percentage of wrapped haylage in the housing diet was below 40%	10		
	[40%; 60%]	Across the GP, the calculated average percentage of wrapped haylage in the housing diet was between 40% and 60%	14		
	> 60%	Across the GP, the calculated average percentage of wrapped haylage in the housing diet was above 60%	12		
GP_duration (day)	< 500 days	The number of days between the weaning and the beginning of the fattening was below 500 days	16		
	> 500 days	The number of days between the weaning and the beginning of the fattening was above 500 days	61		
Nature of pasture	Grass	During above 75% of the pasture period, the heifer diet was only grass	58		

556

557 ¹ SE = standard error.558 ² DM = dry matter.

559

560

561 **Table 3**

562 Description of the rearing factors characterizing the fattening period (FP) (in bold, the rearing factors conserved after the test of
 563 multicollinearity).

Fattening period					
Quantitative rearing factors	Description of the rearing factor		Mean ± SE ¹	Min	Max
Age early fattening (month)	Age of the heifer at the beginning of FP		27.7 ± 0.3	20.4	30.3
Initial weight (kg)	Live weight of the heifer at the beginning of FP		606 ± 6.7	448	779
Slaughter age (month)	Age of the heifer at the slaughter		32.8 ± 0.3	28.3	37.3
Slaughter weight (kg)	Live weight of the heifer before the slaughter		727 ± 6.9	590	873
ADG_FP (kg/day)	Average daily gain of the heifer between the beginning of FP and the slaughter		0.7 ± 0.03	0.19	2.4
Hay_FP (%)	Calculation of the hay percentage in the average diet across the whole FP		55.4 ± 4.1	17.2	100
Grass_silage_FP (%)	Calculation of the grass silage percentage in the average diet across the whole FP		22.0 ± 2.8	0.0	82.8
Wrapped_haylage_FP (%)	Calculation of the wrapped haylage percentage in the average diet across the whole FP		21.7 ± 2.8	0.0	64.6
Forage_CP_FP (g/kg DM ²)	Calculated average of the forage's ³ crude protein content across the whole FP		110.6 ± 3.2	14.4	143.7
Forage_NE_FP (Mcal/kg DM)	Calculated average of the forage's ³ net energy content across the whole FP		1.2 ± 0.01	1.0	1.3
Forage_NDF_FP (g/kg DM)	Calculated average of the forage's ³ neutral detergent fiber (NDF) content across the whole FP		572.6 ± 5.2	510.2	642.3
Conc_quant_intake_FP (kg/day)	Total quantity intake per heifer during FP		786.4 ± 55.5	97.3	1967.4
Conc_NE_FA (Mcal/kg DM)	Calculated average of the concentrate's net energy content the whole FP		1.9 ± 0.01	1.6	2.0
Pasture_duration_FP (day)	Number of days spend at pasture during FP		53.3 ± 8.3	0.0	199.0
FP_duration (day)	Number of days between the beginning of FP and the slaughter		47.0 ± 15.0	201.5	605.0
Qualitative rearing factors	Modalities of the rearing factors	Description of the rearing factor	n		
Conc_CP_FP (g/kg DM)	< 250 g/kg DM	Across the whole FP, the calculated average of concentrate's crude protein content was below 250 g/kg DM	59		
	> 250 g/kg DM	Across the whole FP, the calculated average of concentrate's crude protein content was above 250 g/kg DM	18		
Fattening system	Housing	The fattening was carried out in housing	33		
	Pasture	The fattening was carried out at pasture	15		
	Pasture & Housing	The fattening was started at pasture and then finished in housing	14		
	Outside	The fattening was carried out outside without grass	15		

564

565 ¹ SE = standard error.

566 ² DM = dry matter.

567 ³ Forage = hay + grass silage + wrapped haylage.

568

569

570 **Table 4**

571 Description of the carcass traits and the shear force of the five rib's muscles.

Carcass traits			
Quantitative rearing factors	Mean \pm SE ¹	Min	Max
Cold weight (kg)	425 \pm 4.79	330	509
Dressing percentage (%)	58.5 \pm 0.24	53.6	65.6
Temperature at 24 h (°C)	6.8 \pm 0.11	4.0	9.6
Qualitative carcass traits	Modalities of the carcass traits	n	
Number of carcasses per EUROP class ²			
	E-		3
	U+		24
	U=		28
	U-		16
	R+		6
pH 24 h			
	< 5.8		22
	\geq 5.8		55
Meat traits			
Shear force (N/cm ²)	Mean \pm SE	Min	Max
<i>M. complexus</i>	60.8 \pm 1.75	27.9	110.3
<i>M. infraspinatus</i>	90.7 \pm 3.08	45.5	162.4
<i>M. longissimus</i>	45.2 \pm 1.43	23.7	88.5
<i>M. rhomboideus</i>	61.1 \pm 1.99	13.3	112.9
<i>M. serratus ventralis</i>	54.1 \pm 1.88	31.2	125.3

572

573 ¹ SE = standard error.574 ² The EUROP classes are E+ (extremely muscled), E=, E-, [...], P+, P=, and P- (very poorly
575 muscled).

576

577 **Table 5**

578 Effects of the rearing managements, carcass clusters, muscle and their interaction on the
579 toughness of the meat.

	Shear force (N/cm ²)	
	Emmean ¹	SE ²
Rearing management ³ (RM)		
RM-1	63.2	2.51
RM-2	64.3	3.01
RM-3	60.8	2.36
RM-4	68.7	2.36
Carcass clusters ⁴ (C)		
CARCA-Low	67.9	2.52
CARCA-High	60.6	1.41
Muscles (M)		
M. <i>complexus</i>	62.6	2.16
M. <i>infraspinatus</i>	92.6	2.19
M. <i>longissimus</i>	46.8	2.16
M. <i>rhomboideus</i>	63.0	2.16
M. <i>serratus ventralis</i>	56.2	2.17
P-value		
RM		0.13
C		0.01
M		< 0.001
M x RM		0.007

580

581 ¹ Emmean = estimated marginal means.582 ² SE = standard error.

583 ³ Rearing managements = the four rearing managements considered were defined and
584 described in Soulat et al. (2020).

585 ⁴ Carcass clusters = carcass clusters' traits were defined and described in Soulat et al. (2020).

586

587

588 **Table 6**

589 Equations and performances for the three linear prediction models of shear force (RF_SF model established from only rearing factors,
590 CARCA_SF model established from only carcass traits, and RF&CARCA_SF model established from rearing factors and carcass traits).

Models	Independent variables ¹	Coefficients (\pm SD)	N of significant variables over 500 bootstraps ²	RMSEP ³		R ²		MPE ⁴		AIC ⁵	
				Mean	CI ⁶	Mean	CI	Mean	CI	Mean	CI
RF_SF				18.10	[16.33; 19.91]	0.43	[0.33; 0.52]	0.29	[0.27; 0.32]	3274.89	[3208.68; 3332.71]
	Intercept	127.4 \pm 18.5									
	<i>M. infraspinatus</i>	30.1 \pm 3.4									
	<i>M. longissimus</i>	-15.5 \pm 2.1									
	<i>M. rhomboideus</i>	0.3 \pm 2.5									
	<i>M. serratus ventralis</i>	-6.6 \pm 2.4									
	Age of the cow	-0.9 \pm 0.3	426								
	ADG_GP	-22.6 \pm 6.5	461								
	Slaughter age	-1.0 \pm 0.4	323								
	ADG_FP	-8.5 \pm 2.8	412								
CARCA_SF				17.85	[15.96; 19.70]	0.44	[0.34; 0.53]	0.29	[0.26; 0.31]	3270.30	[3204.22; 3326.68]
	Intercept	122.7 \pm 11.7									
	<i>M. infraspinatus</i>	30.2 \pm 3.4									
	<i>M. longissimus</i>	-15.6 \pm 2.1									
	<i>M. rhomboideus</i>	0.2 \pm 2.4									
	<i>M. serratus ventralis</i>	-6.7 \pm 2.5									
	Cold carcass weight	-0.1 \pm 0.03	496								
	Temperature at 24 h	-2.0 \pm 1.0	294								
RF&CARCA_SF				17.89	[16.07; 19.68]	0.44	[0.35; 0.53]	0.29	[0.26; 0.31]	3259.63	[3200.82; 3313.81]

Intercept	128.1 ± 11.7	
M. <i>infraspinatus</i>	30.2 ± 3.6	
M. <i>longissimus</i>	-15.4 ± 2.2	
M. <i>rhomboideus</i>	0.5 ± 2.5	
M. <i>serratus ventralis</i>	-6.5 ± 2.6	
Age of the cow	-0.8 ± 0.3	372
Cold carcass weight	-0.1 ± 0.02	499
Temperature at 24 h	-2.0 ± 1.0	316

591

592 ¹ For the explanation of the models' independent variables please refer to the following tables: Tables 1 to 3 for the rearing factors, and Table 4
593 for the carcass traits.

594 ² Number of times the independent variables were significant in the model over 500 bootstraps.

595 ³ RMSEP = root mean square error of prediction.

596 ⁴ MPE = mean prediction error.

597 ⁵ AIC = Akaike information criterion.

598 ⁶ CI = confidence interval.

599

Fig. 1. Summary of the four rearing managements **applied during the heifers' whole life defined by** Soulat et al. (2020) (ADG = average daily gain; Tot_duration_CC = total time spent by the calf with her mother between the birth and the weaning; Conc_duration = number of days of offered concentrates in the diet; Conc_quant_i_intake = average daily quantity intake per heifer, Conc_NE = calculated average of concentrate's net energy content; Conc_CP = calculated average of concentrate's crude protein content; Forage_CP = calculated average of the forage's crude protein content; Forage_NDF = calculated average of the forage's neutral detergent fiber content).

Rearing management (RM)

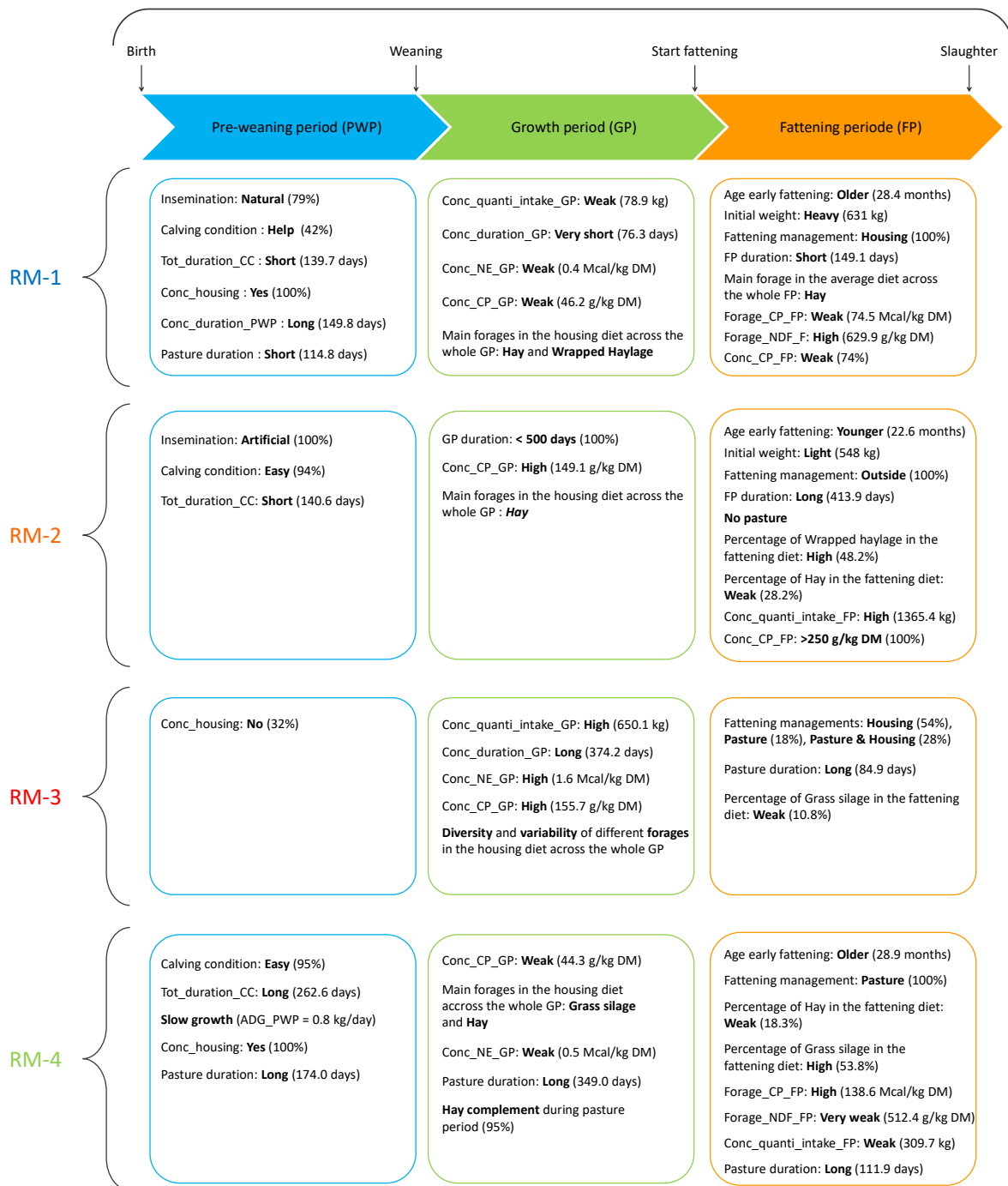
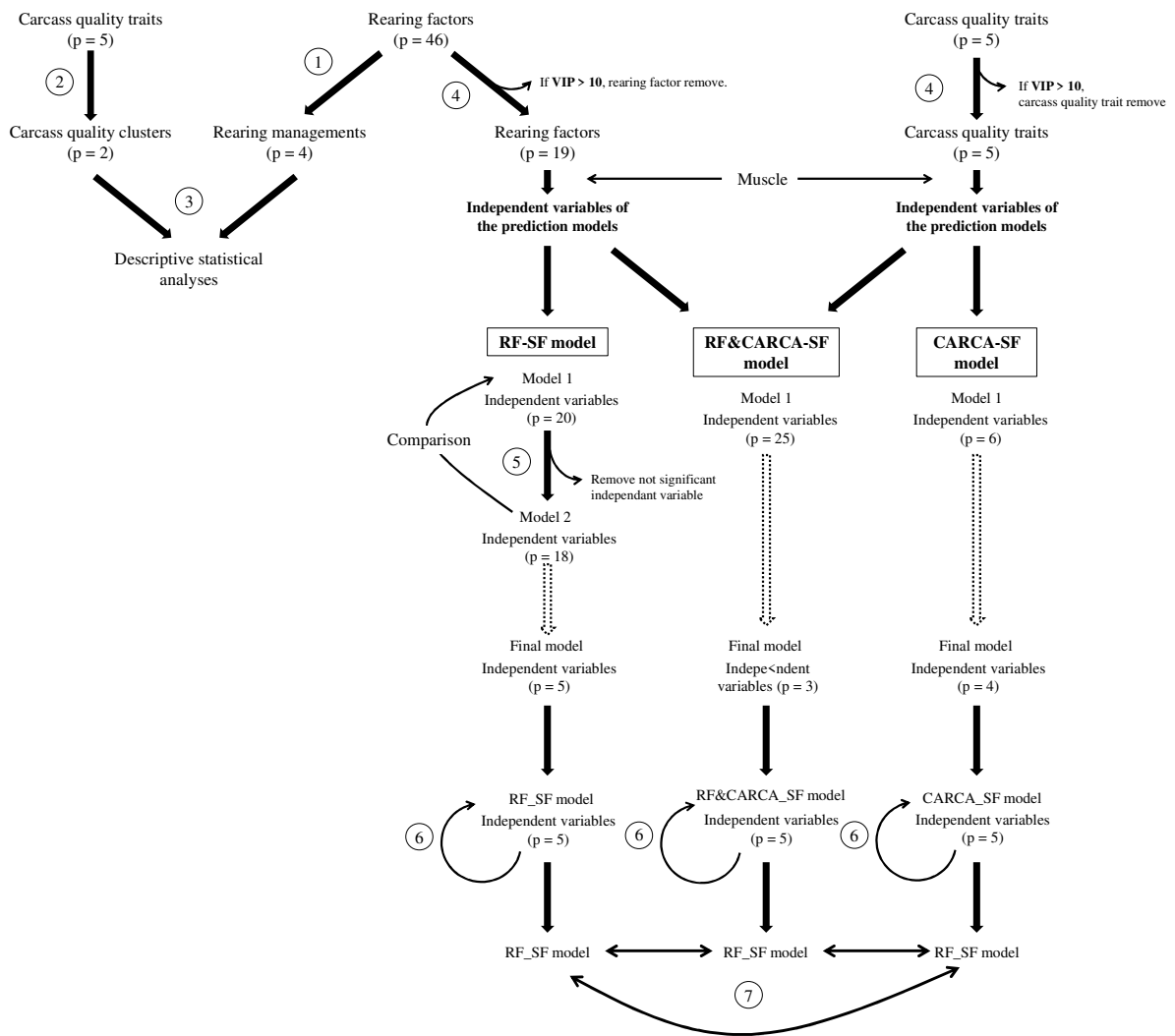


Fig. 2. Framework of the statistical procedures performed in this study: descriptive and predictive analyses (RF: rearing factor, CARCA: carcass, SF: shear force).



- Descriptive analyses**
- Determination of the rearing managements (using a **factor analysis for mixed data** following then a **hierarchical clustering on principal components**).
 - Determination of the carcass quality clusters (using a **factor analysis for mixed data** following then a **hierarchical clustering on principal components**).
 - Performing of the ANOVA.
- Predictive analyses**
- Multicollinearity test (using the variance inflation factors, **VIF**).
 - Establishment of the prediction model (using **linear regression**).
 - If $Model_a = Model_{a+1}$, the independent variable could be removed.
 - If $Model_a \neq Model_{a+1}$, the independent variable could not be removed.
 - Validation of the prediction model (using **bootstrap**).
 - Comparison of prediction quality between RF_SF, RF&CARCA_SF, and CARCA_SF models (using the following parameters: R^2 , RMSEP, MPE, and AIC).
- The point (5) was repeated to the final model.

p : number of parameters/variables included.

Fig. 3. Effect of the interaction between the rearing managements (RM) and the muscles (*M. complexus*, CP; *M. infraspinatus*, IF; *M. longissimus*, LM; *M. rhomboideus*, RH; and *M. serratus ventralis*, SV) on the shear force of raw meat. ^{a,b,c,d,e,f}Estimated marginal means (emmeans) in different letters were significantly different ($P < 0.05$).

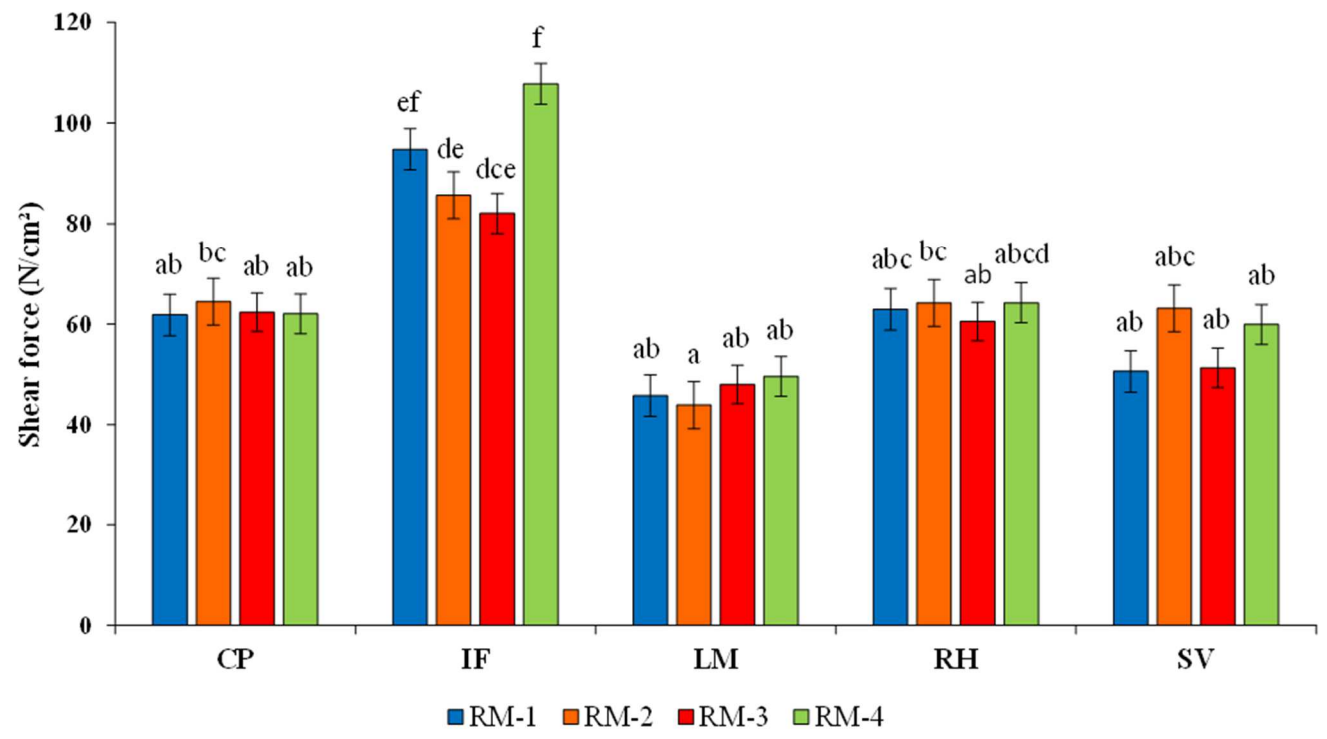


Fig. 4. Principal component analysis of shear force of the raw five rib's muscles (*M. complexus*, CP; *M. infraspinatus*, IF; *M. longissimus*, LM; *M. rhomboideus*, RH; and *M. serratus ventralis*, SV).

