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## Forensic use of the genomic relationship matrix to validate and discover livestock pedigrees

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1 Running head: Genomic pedigree validation and discovery

2

3 Forensic use of the genomic relationship matrix to validate and discover livestock pedigrees

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5

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7

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9 providing access to their pedigree and genotype database.

10

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12

## 13 **Abstract**

14           Correct pedigree is essential to produce accurate genetic evaluations of livestock  
15 populations. Pedigree validation has traditionally been undertaken using microsatellites and  
16 more recently, based on checks on opposing homozygotes using Single Nucleotide  
17 Polymorphisms (SNPs). In this study, the genomic relationship matrix was examined to see if  
18 it was a useful tool to forensically validate pedigree and discover unknown pedigree. Using  
19 5,993 genotyped Limousin animals which were imputed to a core set of 38,907 SNPs, the  
20 genomic relationships between animals were assessed to validate the reported pedigree.  
21 Using already pedigree verified animals, the genomic relationships between animals of  
22 different relationships were shown to be on average 0.58, 0.59, 0.32, 0.32, 0.19 and 0.14  
23 between animals and their parents, full siblings, half siblings, grandparents, great  
24 grandparents and great great grandparents, respectively. Threshold values were defined based  
25 on the minimum genomic relationship reported between already pedigree verified animals;  
26 0.46, 0.41, 0.17, 0.17, 0.07 and 0.05, respectively for animals and their parents, full siblings,  
27 half siblings, grandparents, great grandparents and great great grandparents. Using the wider  
28 population and the above genomic relationship threshold values, potential pedigree conflicts  
29 were identified within each relationship type. Pedigree error rates of between 0.9% (animal  
30 and great great grandparent) and 4.0% (full siblings) were identified. A forensic genomic  
31 pedigree validation and discovery system was developed to enable pedigree to be verified for  
32 individual genotyped animals. This system verifies not just the parents, but also a wide  
33 number of other genotyped relatives and can therefore identify more potential errors in the  
34 pedigree than current conventional methods. A novel aspect to this algorithm is that it can  
35 also be used to discover closely related animals on the basis of their genomic relationships  
36 although they are not recorded as such in the pedigree. This functionality enables missing  
37 pedigree information to be discovered and corrected in the pedigree of livestock populations.

38 The methods in this paper demonstrate that the genomic relationship matrix can be a useful  
39 tool in the validation and discovery of pedigree in livestock populations. However, the  
40 method does rely on being able to define threshold values appropriate to the specific livestock  
41 population, which will require sufficient number of animals to be genotyped and pedigree  
42 validated before it can be used.

43

#### 44 **Key words**

45 genomic relationship matrix, pedigree discovery, pedigree verification

46

#### 47 **Introduction**

48 Genetic evaluations in the UK are undertaken using Best Linear Unbiased Prediction  
49 (BLUP) techniques (Henderson, 1973). In addition to phenotypic information, a relationship  
50 matrix is constructed based on recorded pedigree information. Therefore, correct knowledge  
51 of pedigree is essential for accurate genetic evaluations. However, pedigree errors in  
52 livestock populations are common with significant error rates reported in sheep, beef and  
53 dairy populations (Kaseja et al., 2018; Spelman, 2002). Visscher et al., (2002) for UK dairy  
54 cows estimated an overall pedigree error rate of 10% and predicted this would result in a loss  
55 of selection response of 2 to 3%. For the same pedigree error rate, Israel and Weller, (2000)  
56 predicted a 4.3% loss in genetic response. Banos et al., (2001) showed that with 11%  
57 pedigree errors there was a reduction in the Estimated Breeding Values (EBVs) genetic  
58 trends of 11 to 18%.

59 To improve the accuracy of the pedigree, molecular techniques can be used for  
60 parentage verification. Until recently, microsatellite markers were the standard approach to  
61 parentage verification (Davis and DeNise, 1998). The international standard has been to use  
62 12 International Society of Animal Genetic (ISAG) markers

63 ([http://www.isag.us/Docs/CattleMMPTest\\_CT.pdf](http://www.isag.us/Docs/CattleMMPTest_CT.pdf)). With the introduction of Single  
64 Nucleotide Polymorphisms (SNP) and genomic selection (Meuwissen et al., 2001), SNP  
65 based parentage methods are now becoming the standard approach. The international  
66 standard has been to use the ISAG100 or ISAG200 SNP set, however McClure et al., (2015)  
67 has suggested that a panel with a minimum of 500 SNPs is more appropriate for parentage  
68 verification and prediction.

69 To date most pedigree verification has focused on the animal – parent relationship  
70 although Van Raden et al., (2013) and Wiggans et al., (2018) have both reported methods to  
71 assess the validity of animal – grandparent relationships using SNP based approaches.  
72 Considering relationships other than animal – parent could be advantageous as often the  
73 females in the population are not well genotyped but the maternal grandsires often are.  
74 Huisman (2017) used likelihood methods applied to SNP genotype markers to reconstruct  
75 pedigree in a number of simulated and empirical datasets of wildlife populations. This study  
76 found a wide range of relationship types useful to construct the pedigree, and developed an R  
77 package to do so. However the likelihood methods are computationally demanding and not  
78 able to compute for large datasets often observed in livestock populations. The study also  
79 showed generally strong positive correlations between the relationship matrix from the  
80 constructed pedigree and the genomic relationship matrix (GRM).

81 The GRM is required for genomic selection and much research attention has been on  
82 how to construct and invert the matrix and the impact of this on the resulting genetic  
83 evaluations and their accuracies (Chen et al., 2011; Habier et al., 2007; Jimenez-Montero et  
84 al., 2013; Koivula et al., 2012; Muir, 2007; Van Raden, 2007; 2008). However, little focus  
85 has been placed on whether the GRM could be a useful tool to validate and discover  
86 parentage for livestock populations. Grashei et al., (2018) considered the GRM in a  
87 simulation and assigned genomic relationship likelihood values to verify and discover sets of

88 parentage trios based on thresholds specific to genotype error rates of 1 and 3%. This  
89 approach assumed both parents were genotyped and considered verified parent – offspring  
90 relationships. In a chicken population, Wang et al., (2014) compared the GRM with the  
91 pedigree numerator relationship matrix (NRM). This study found where populations had long  
92 and complete pedigree recorded, clean genotypes and proper scaling applied to the GRM that  
93 the relationship coefficient from the NRM and GRM were in strong agreement. Recently,  
94 human forensic investigators have successfully used genomic relationships using DNA left at  
95 crime scenes and genotypes stored in human genealogical databases to identify suspects and  
96 solve previously unsolved cases (Ram et al., 2018). Often the perpetrator themselves do not  
97 have a genotype stored in these databases, but the suspect is identified based on identifying  
98 cousins and other close relatives – with relatives on the maternal and paternal side of the  
99 pedigree, this approach can identify a single family group to consider more closely to identify  
100 potential suspects.

101 The objective of this paper was to use genotypes from a UK beef population to  
102 construct a GRM and assess if it was a useful tool to forensically validate and discover  
103 missing pedigree to improve the accuracy of the pedigree, and thus ultimately the accuracy of  
104 genetic evaluations. In particular, we wanted to assess if the genomic relationships between  
105 more distantly related animals i.e. half sibs and grandparents could be used to verify pedigree  
106 involving un-genotyped parents.

107

## 108 **Materials and Methods**

109 After removing duplicate genotypes and genotypes with a call rate of less than 90%,  
110 5,993 genotyped animals were available from a UK pedigree Limousin beef population. The  
111 dataset consisted of 1,942, 1,790, 1,494 and 767 animals genotyped with Illumina 50k, High  
112 density, International Dairy and Beef (IDB) 50k and IDB 14k SNP panels, respectively.

113 Previous unpublished work on this population undertook a principal component analysis  
114 which confirmed the genotyped population to be purebred without any cross bred and  
115 animals from another breed present in the genotyped population. Pedigree was available for  
116 these animals from a national bovine pedigree which included pedigree from pedigree  
117 Society databases, national British Cattle Movement Service (BCMS) data and milk  
118 recording organisations. On average, 7 generations (range = 1 to 14) of pedigree were  
119 available for genotyped animals. In almost all cases where pedigree is reported, both the sire  
120 and dam are reported as this is a breed society requirement. For 87% of the genotyped  
121 animals there were 4 or more generations of complete pedigree available. Inbreeding  
122 coefficients were computed using RelaX2 software (Stranden and Vuori, 2006) for all  
123 animals available in the national bovine pedigree, with no restriction placed on the number of  
124 generations of pedigree or genotype status. However the inbreeding results are reported only  
125 for the genotyped animals.

126 A panel of 116 USDA parentage SNPs was used to verify the reported parentage of  
127 the genotyped animals using opposing homozygotes (Hayes, 2011) where both parent and  
128 offspring were genotyped. Animal – parent combinations with more than 2 inconsistencies  
129 were considered to fail parentage verification.

130 All genotypes were imputed using the program Findhap Version 3 (Van Raden et al.  
131 2011) to a core set of 38,907 SNPs currently used for the national genomic evaluations.  
132 These SNPs were selected based on minor allele frequencies greater than 0.05 and SNP call  
133 rates greater than 0.90, and included the parentage SNPs where they passed the inclusion  
134 criteria. The average minor allele frequency in the core SNP subset was 0.28. Using this set  
135 of imputed genotypes, a GRM was constructed using Van Raden's (2008) first method with  
136 the GRM scaled using the current population allele frequencies.

137

138 *Analysis of GRM to validate pedigrees*

139           Pairwise genomic relationship coefficients between genotyped animals that passed  
140 parentage verification using the SNP based opposing homozygote approach were extracted,  
141 summarized and reported for animals with their respective parents, grandparents, great  
142 grandparents, great great grandparents, full siblings and half siblings. The genomic  
143 relationship coefficients obtained gave a range of accepted genomic relationship coefficients  
144 for each of the different pedigree relationship categories. For example, to contribute to the  
145 animal – grandparent category the animal – parent and parent – grandparent relationship  
146 needed to be verified based on the SNP based opposing homozygote method. This was  
147 undertaken for all animals that met the criteria to contribute to the specific categories and  
148 then again using only animals where both animals in the pairwise comparison had inbreeding  
149 coefficients less than 7%.

150           This method was then applied to the wider genotyped population regardless of their  
151 pedigree verification status, provided both animals in the pair combination were genotyped.  
152 The pairwise relationship was deemed to have failed validation where the genomic  
153 relationship was lower than the minimum genomic relationship coefficient reported in the  
154 subset of genotyped animals pedigree verified from SNP based opposing homozygote  
155 method.

156           To verify un-genotyped sires and dams, genomic relationships within paternal and  
157 maternal half sibling family groups were compared, respectively. Again, the minimum  
158 genomic relationship coefficient reported for half siblings from the subset of previously  
159 pedigree verified genotyped animals was used to assess if the true relationship between the  
160 animals was in line with that of half siblings. This information, along with the number of  
161 genotyped animals in the half sibling family, was used to assess if the reported un-genotyped  
162 parent could be considered as being correct. An alternative method of assessing the accuracy



163 of a un-genotyped reported parent was to compare the genomic relationship between animals  
164 and their grandparents. Again the threshold for acceptance was the reported minimum  
165 genomic relationship for animal – grandparent from the study using only animals previously  
166 pedigree verified using SNP based methods.

167 For a given genotyped animal, all the genomic relationship coefficients between that  
168 animal and the wider genotyped population were used to produce a forensic genomic  
169 pedigree validation and discovery report. This report grouped animals based on the reported  
170 pedigree relationships into the following family groups; progeny, parents, grandparents, great  
171 grandparents, great great grandparents, full siblings, paternal and maternal half siblings,  
172 aunts/uncles, great aunts/uncles, great great aunts/uncles, nieces/nephews and 1<sup>st</sup> cousins. The  
173 genomic relationship coefficients between the given animal and their relatives were reported  
174 along with a marker showing if the genomic relationship coefficient is above or below the  
175 appropriate minimum relationship observed from the analysis using only animals previously  
176 pedigree verified. To assist with the forensic discovery of unknown pedigree, the report also  
177 ranked animals that were not in reported pedigree relationships or have genomic relationship  
178 coefficients inconsistent with the reported pedigree relationship into three candidate lists for  
179 consideration; 1. Likely to be a close relationship akin to grandparent, sibling, parents, 2.  
180 Those likely to be more distantly related, i.e. great grandparents and 3. Those not closely  
181 related. Studying these lists, in particular the close relationship list, can frequently lead to the  
182 discovery of missing pedigree information. To test potential candidates, the report has a  
183 function where parent information can be substituted, or set to unknown, and the genomic  
184 relationship coefficients of all genotyped relatives tested given the suspected true pedigree.

185

## 186 **Results and Discussion**

187           Using the 116 USDA parentage SNPs and opposing homozygotes, half (50.1%) of the  
188 genotyped animals in the dataset were able to be validated for the animal – parent  
189 relationship. In total 2,918 (48.7%) animals had the reported sire and/or dam confirmed with  
190 less than 2 SNP inconsistencies observed; the breakdown for these animals were 2,507 sire  
191 only, 162 dam only and 249 both sire and dam verified. There were 81 (1.4%) animals where  
192 the parentage was inconsistent with that reported in the pedigree; the breakdown for these  
193 animals were 77 sire only, 2 dam only and 2 both sire and dam inconsistent. With only 1.4%  
194 of animals having inconsistent pedigree reported, the level of pedigree errors for these  
195 genotyped animals was very low compared to levels reported in livestock populations (Kaseja  
196 et al., 2018; Spelman, 2002; Visscher et al., 2002). This can be attributed to the breed society  
197 policy requiring any bull sold at a society bull sale to be sire verified and any embryo transfer  
198 calf registered to have both sire and dam verified and correct pedigree reported in the  
199 database. The genomic relationship coefficient for the genotyped animals with themselves  
200 was on average 1.12 and ranged from 1.01 to 1.71. The pedigree based inbreeding  
201 coefficients for these animals averaged 0.01 and ranged from 0.0 to 0.33. The genomic  
202 relationship with self may be higher than 1.0 where an animal is inbred (Grashei et al., 2018)  
203 or there are SNPs that are identical by state rather than identical by descent. The genomic  
204 relationship between sires and dams for the 249 genotyped progeny where both parents were  
205 also genotyped was on average 0.09, but ranged from 0.02 to 0.30. The mating pairs were  
206 generally between non-related animals with only 14 of these progeny having a pedigree based  
207 inbreeding coefficient greater than 7%. The average inbreeding coefficient was 0.02 with a  
208 range of 0.0 to 0.14 for the 249 animals with both parents genotyped.

209           The pairwise genomic relationship coefficients were summarised for animals where  
210 the reported pedigree relationship was verified using the USDA parentage SNPs. This was  
211 undertaken for all verified animals and then for only those with pedigree inbreeding

212 coefficients less than 7% and these results are reported in Table 1. For all relationship type  
213 categories the average genomic relationship coefficient was higher than the value  
214 theoretically expected by between 7 and 9%. For example, animal – parent and animal – full  
215 sibling relationships are expected to have 50% of genes in common but in our study we saw  
216 the average genomic relationship ranging from 0.57 to 0.59. This increase is of the same  
217 magnitude to the genomic relationships between sires and dams from the 249 matings where  
218 both parents were genotyped. Animals that were inbred had higher genomic relationships  
219 compared to those that were not. However, there was no difference for the minimum genomic  
220 relationships observed within a relationship type category. It is these minimum genomic  
221 relationship coefficients that were used as threshold values to assess the validity of reported  
222 pedigree later in the study. Since inbreeding levels did not affect the minimum genomic  
223 relationship category it can be considered that the inbreeding level of the animals will not  
224 affect the conclusions drawn about the possibility of the reported pedigree. With only 83 full  
225 sibling pairs available, the minimum genomic relationship coefficient (0.46) was higher than  
226 that of animal – parent (0.41) relationships. This is likely to be due to the small sample size  
227 and not because of a true difference in ranges. Given the theoretical level of relatedness is the  
228 same for both relationship type categories and the low number of full siblings to establish a  
229 minimum threshold value, it is appropriate to use the minimum genomic relationship for  
230 animal – parents also for full siblings. The maximum genomic relationship coefficient within  
231 relationship type categories is not as robust to assess the likelihood of the reported pedigree  
232 being correct. This is because as seen in Table 1, inbreeding can inflate the genomic  
233 relationship coefficient but also the maximum coefficient is similar for the more distant  
234 relationships. For example, the maximum coefficient for animal – grandparent is similar to  
235 that of animal – great grandparent, while the minimum coefficients were sufficiently  
236 different. However, when looking at individual animals with the forensic genomic pedigree

237 validation and discovery report, comparing the reported coefficient with the appropriate  
238 relationship type maximum genomic relationship coefficient may be useful. The genomic  
239 relationship ranges reported in this paper are based on this population with population  
240 specific inbreeding and genetic diversity levels likely to affect the ranges observed. Therefore  
241 to apply this method to other populations, base line thresholds should first be assessed within  
242 the specific population.

243 For all reported pedigree relationships the genomic relationship coefficients are  
244 reported in Table 2. The average genomic relationship coefficient within relationship type  
245 categories were very similar to those reported in Table 1 for previously pedigree verified  
246 animals, as were the maximum genomic relationship values. For the full sibling category  
247 there was a set of identical twins, which as expected had a genomic relationship akin to that  
248 of the animal to itself. A pairwise comparison was considered inconsistent where the genomic  
249 relationship coefficient was below the minimum genomic relationship coefficient reported in  
250 Table 1. For example, there were 186 animal – grandparent pairs with a genomic relationship  
251 less than 0.17 and thus likely to be not be related at the animal – grandparent level. Across all  
252 relationship type categories there were between 0.9% (animal – great great grandparent) and  
253 4.0% (full siblings) relationships that were considered to be inconsistent.

254 Un-genotyped sires and dams were potentially verified by examining the paternal and  
255 maternal half sibling family groups. Of the half sibling relationships reported in Table 2,  
256 59,630 were the result of sharing the same sire and this represented 623 different sires with  
257 the number of progeny pairs ranging from 1 (2 progeny) to 14,365 (170 progeny). Using the  
258 minimum value for half siblings (0.17) reported in Table 1 there were 1,596 half sibling pairs  
259 which had a genomic relationship coefficient inconsistent with that reported in the pedigree.  
260 These inconsistencies involved 69 different sires and in some cases it was just 1 pair of half  
261 siblings involved and at the other extreme there were 245 pairs of half siblings for the sire

262 that were inconsistent. In this extreme case, the reported sire was a popular AI sire with 124  
263 progeny genotyped generating 7,626 half sibling pairs to test. The 245 pairs that were  
264 inconsistent involved just 2 of his genotyped progeny. Although the sire himself was not  
265 genotyped, and thus it was not possible to test parentage using conventional methods, given  
266 the large volume of half siblings we can with reasonable confidence consider that the  
267 reported AI sire is not the true sire of the 2 animals involved in the failed half sibling pairs.  
268 However, this sire is likely to be the true sire for the other 122 genotyped progeny. For the  
269 maternal half sibling family groups there were 2,313 half sibling pairs to compare. These  
270 were the result of 529 different dams with the number of progeny pairs ranging from 1 (2  
271 progeny) to 210 (21 progeny). There were 43 maternal half sibling pairs that were considered  
272 inconsistent, involving 17 dams. Again the number of inconsistent comparisons per dam  
273 ranged from 1 to 8. While the interpretation is identical for both paternal and maternal half  
274 sibling groups this analysis is better suited to verifying un-genotyped sires due to the larger  
275 size of paternal half sibling family groups compared to that for the maternal half sibling  
276 family groups. It was not clear exactly how many genotyped half siblings were needed to  
277 verify an un-genotyped parent. For those sires and dams with small family groups, this  
278 method alone may not be able to verify the pedigree but could identify which sires and dams  
279 need genotyping to confirm parentage if there are inconsistencies found. For those sires and  
280 dams with larger family groups, the reported parent may not need to be genotyped in order to  
281 draw conclusions about the true parentage of progeny. This is especially beneficial where  
282 DNA for the candidate parents is unable or too expensive to be obtained.

283         An alternative approach for verifying the pedigree of animals was to consider the  
284 animal – grandparent relationship. Table 2 shows that for the relationship type there were 186  
285 (3.6%) animal – grandparent pairs that were below the threshold of 0.17. Having an  
286 inconsistent animal – grandparent genomic relationship coefficient does not automatically

287 mean that the reported parent is incorrect, as it could be that the reported parent is correct and  
288 the error is in fact between the parent – grandparent relationship. This approach can be  
289 applied equally to reported sires and dams, and in fact could be more beneficial for the  
290 maternal side of the pedigree as females are often not genotyped in the same volume as  
291 males. Testing the animal – grandparent relationship can also detect general issues with  
292 genotyping earlier. An example of where testing the animal – grandparent relationship can  
293 detect genotyping issues earlier is where samples for paternal half siblings are accidentally  
294 swapped during the sampling and genotyping process. With animal – parent testing, both  
295 samples will be correctly parent verified as they share a common sire. However it will not be  
296 until the half siblings themselves have progeny, and the progeny subsequently fail the  
297 parentage testing process that the accidental genotype swap will be identified. Testing the  
298 animal – maternal grandparent relationship will detect that the maternal grandsire is not as  
299 reported and the issue can then be identified and resolved at the time of the animal being  
300 genotyped rather than when the next generation of animals are being genotyped and DNA  
301 from the sire potentially harder to obtain.

302         The forensic genomic pedigree validation and discovery report provides, for a single  
303 animal, information on related animals (those reported in the pedigree and those that are  
304 related but not recorded in the pedigree) and details of an example animal are provided in  
305 Table 3. For the animal being considered in Table 3, it was detected that despite the reported  
306 dam not being genotyped, there was an error on the maternal side of the pedigree and that the  
307 reported paternal pedigree appeared to be correct. Furthermore, discovering candidate  
308 maternal grandparents was possible which led to the discovery of the correct dam. The  
309 success of the report in forensically discovering and correcting pedigree is dependent of the  
310 size of the genotyped population – where there are more genotypes the more successful the  
311 process will be in identifying and correcting pedigree issues. The pedigree discovery process

312 also requires a level of interpretation and sense checking based on the year of birth and  
313 gender of animals involved. There is also the potential for inferring a closer than actual  
314 relationship if the genotyped animal is inbred with ancestors occurring several times in the  
315 pedigree (i.e. double grandparent). This can be mitigated by considering all the relationships  
316 reported in the report and being aware of the possibility of this occurring.

317         The presented methods for forensically validating and correcting pedigrees have been  
318 shown to be useful tools for cleaning and enriching pedigrees used in genetic evaluations.  
319 Despite this dataset having a relatively low number of parentage errors as a result of the breed  
320 societies routine parentage testing scheme, there were still additional pedigree conflicts that  
321 were identified in the genotyped dataset. It is likely that the number of pedigree conflicts  
322 would be substantially higher in a livestock population that does not already have a stringent  
323 pedigree verification scheme and it would be interesting to apply these methods to other  
324 livestock populations for comparison. A limitation to the application of these methods in  
325 other populations will be establishing robust minimum thresholds values that are used to  
326 differentiate the different relationship types. While the thresholds have been robust during  
327 testing for parent and grandparent relationship levels, with minimum threshold values of 0.07  
328 and 0.05 reported for great and great great grandparents, respectively, a degree of caution  
329 should be applied when interpreting the genetic relationships for more distant ancestors as it  
330 is possible for unrelated animals to also have these genetic relationships.

331         The methods used to construct the GRM will also impact on the genomic relationship  
332 coefficients. The NRM is constructed based on pedigree alone and assumes that the founder  
333 animals in the recorded pedigree are unrelated, which is usually not the case. Whereas the  
334 GRM is based only on the genotypes and captures the relationships between animals  
335 regardless of what is recorded in a pedigree. This means that each method uses a different  
336 base population which can result in different relationship coefficients (Wang et al., 2014).

337 The genomic relationship coefficients from the GRM are influenced by the SNP chip density  
338 and platform, the level of QA applied to the genotypes, in particular to the minor allele  
339 frequencies (Chen et al., 2011; Forni et al., 2011; Van Raden 2008; Wang et al., 2014).  
340 Applying appropriate QA to the genotypes and constructing the GRM so it is scaled using the  
341 observed allele frequencies should result in a GRM comparable to the NRM with differences  
342 in reported coefficients due to errors in the reported pedigree (Chen et al., 2011; Forni et al.,  
343 2011; Van Raden 2008).

344

### 345 **Conclusion**

346 This study has shown how analysis and interpretation of the genetic relationship coefficients  
347 reported from the genomic relationship matrix can be used to validate reported pedigree and  
348 in some cases discover the missing pedigree information. Pedigrees of un-genotyped relatives  
349 were also shown to be possible depending on the number of genotyped relatives available for  
350 comparisons. Applications of these methods to genotyped populations will be able to identify  
351 more pedigree errors than using the current animal – parent SNP based opposing homozygote  
352 approaches and this will ultimately improve the accuracy of genetic evaluations and thus  
353 increase the genetic gain achieved within these livestock populations.

354

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425

426 **Table 1: Genomic relationship coefficients between all animals and those animals with inbreeding coefficients <7%, and that have been**  
 427 **pedigree verified using Single Nucleotide Polymorphism based opposing homozygote methods.**

Relationship Type	Theoretical relationship	Allowed inbreeding coefficient 0-100%					Allowed inbreeding coefficient 0-7%				
		N <sup>1</sup>	Avg <sup>1</sup>	Std <sup>1</sup>	Min <sup>1</sup>	Max <sup>1</sup>	N <sup>1</sup>	Avg <sup>1</sup>	Std <sup>1</sup>	Min <sup>1</sup>	Max <sup>1</sup>
Parents	0.5	3167	0.58	0.03	0.41	0.86	2991	0.58	0.03	0.41	0.71
Grandparents	0.25	1797	0.32	0.05	0.17	0.67	1684	0.32	0.04	0.17	0.49
Great grandparents	0.125	1083	0.19	0.05	0.07	0.7	1017	0.19	0.04	0.08	0.44
Great great grandparents	0.06	256	0.14	0.04	0.05	0.32	248	0.14	0.04	0.05	0.32
Full siblings	0.5	83	0.59	0.06	0.46	0.75	67	0.57	0.05	0.46	0.69
Half siblings	0.25	27625	0.32	0.04	0.17	0.57	24407	0.32	0.04	0.17	0.56

428 <sup>1</sup> N is the number of relationship pairs contributing to the category; Avg is the average genomic relationship coefficient; Std is the standard  
 429 deviation genomic relationship coefficient; Min is the minimum genomic relationship coefficient; Max is the maximum genomic relationship  
 430 coefficient.

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432

433 **Table 2: Genomic relationship coefficients between all animals in the genotyped population based on the reported pedigree information.**

<b>Relationship Type</b>	<b>Theoretical relationship</b>	<b>N<sup>1</sup></b>	<b>Avg<sup>1</sup></b>	<b>Std<sup>1</sup></b>	<b>Min<sup>1</sup></b>	<b>Max<sup>1</sup></b>	<b>% below threshold<sup>2</sup></b>
Parents	0.5	3250	0.57	0.08	0.03	0.71	2.5
Grandparents	0.25	5184	0.32	0.07	0.01	0.86	3.6
Great grandparents	0.125	7819	0.19	0.05	0.02	0.76	1.7
Great great grandparents	0.06	8720	0.14	0.05	0.01	0.65	0.9
Full siblings	0.5	827	0.56	0.08	0.07	1.09	4.0
Half siblings	0.25	60289	0.30	0.06	0.01	0.80	2.9

434 <sup>1</sup> N is the number of relationship pairs contributing to the category; Avg is the average genomic relationship coefficient; Std is the standard  
 435 deviation genomic relationship coefficient; Min is the minimum genomic relationship coefficient; Max is the maximum genomic relationship  
 436 coefficient.

437 <sup>2</sup> the threshold applied is the minimum genomic relationship coefficient reported in Table 1 for each relationship type category.

438

439 **Table 3: Case study of available information in the pedigree verification and discovery report for an individual animal born in 2014.**

<b>Relationship type</b>	<b>Information captured in the pedigree verification and discovery report and its interpretation</b>
Progeny	There are 20 progeny, 1 of which is genotyped with a genomic relationship coefficient of 0.57 - which is above the minimum animal - parent threshold of 0.41.
Parents	None genotyped, but from paternal half sibling information there is reasonable confidence that the reported sire is correct.
Paternal half siblings	There are 61 paternal half siblings with genomic relationship coefficients ranging from 0.26 to 0.37, all these half siblings are above the minimum threshold of 0.17, supporting that they truly are half siblings. From this information we can then be reasonably confident that the reported sire is correct, even though we do not have the sire's genotype available to test.
Grandparents	Both paternal and maternal grandsires are genotyped with genomic relationship coefficients of 0.34 and 0.05, respectively. The lower than 0.17 threshold suggests that the reported maternal grandsire is not the true grandsire. This could be that the sire of the dam is incorrect, or that the dam has been incorrectly recorded.
Great grandparents	There are 4 in total genotyped. On the paternal side, both parents of the paternal grandsire are genotyped with genomic relationship coefficients of 0.18 and 0.23 for the great grand sire and great grand dam, respectively.  On the maternal side, both great grand sires are genotyped and have genomic relationship coefficients of 0.07 and 0.06, both of which is lower than the threshold of 0.07 suggesting they may not be true great grandparents. This suggests that both the

	sire and dam of the animals dam are incorrect, or that the dam has been incorrectly reported.
Great great grandparents	There were 2 genotyped. On the paternal side, a great great grand sire had a genomic relationship coefficient of 0.15, and on the maternal sire, the great great grand sire genomic relationship coefficient =0.11. Both of these animals have values above the threshold of 0.05 suggesting that these may be the true relationships. However, at this distant a relationship it is also possible that they are not related since unrelated animals have been shown to have average genomic relationships of 0.09.
Half aunts/uncles	There were 56 genotyped aunts/uncles based on the pedigree. When tested, there were 45 with genomic relationship coefficients ranging from 0.125 to 0.32, and above the threshold of 0.125 (half aunt/uncle) and 11 which have genomic relationship coefficients of 0.04 to 0.08 and thus unlikely to be an aunt/uncle. A high level of failures here is expected when an grandparent has been incorrectly recorded.
Half niece/nephews	There were 11 genotyped niece/nephews based on the pedigree. When tested, there were 10 with genomic relationship coefficients ranging from 0.16 to 0.26, and above the threshold of 0.125 (half niece/nephews) and 1 which has a genomic relationship coefficient of 0.09 and thus unlikely to be an niece/nephews. A high level of failures here is expected when an parent has been incorrectly recorded.
Potential close relatives	There were 36 reported with genomic relationship values of 0.17 and higher, suggesting they are closer relatives. The top 4 animals in the list and the outcome of investigation is listed; <ol style="list-style-type: none"> <li>1. genomic relationship coefficient =0.40 – a female born in 1998. Given the age range and genetic relationship it is</li> </ol>

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possible that she is the dam, but more likely the grand-dam of animal.

2. genomic relationship coefficient =0.31 – a paternal sibling that was incorrectly recorded in the pedigree.
3. genomic relationship coefficient =0.30 – a paternal sibling that was incorrectly recorded in the pedigree.
4. genomic relationship coefficient =0.29 – a male born in 2001. Given the age range and genetic relationship it is possible that he is the grand-sire of animal.

After discussion with the breeder it was identified that matings between animals 1 and 4 on the list did occur and he supplied some candidate dams to test and it was confirmed that the pedigree recorded for the dam was incorrect, and after DNA verification was corrected to be the correct dam, which was a daughter of animals 1 and 4 in the above list.

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