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1 Automatic early warning of tail biting in pigs: 3D cameras can detect lowered
2 tail posture before an outbreak

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18 Early warning of pig tail biting: 3D cameras detect low tail posture

19 **Abstract**

20 Tail biting is a major welfare and economic problem for indoor pig producers worldwide. Low tail
21 posture is an early warning sign which could reduce tail biting unpredictability. Taking a precision
22 livestock farming approach, we used Time-of-flight 3D cameras, processing data with machine
23 vision algorithms, to automate the measurement of pig tail posture. Validation of the 3D
24 algorithm found an accuracy of 73.9% at detecting low vs. not low tails (Sensitivity 88.4%,
25 Specificity 66.8%). Twenty-three groups of 29 pigs per group were reared with intact (not docked)
26 tails under typical commercial conditions over 8 batches. 15 groups had tail biting outbreaks,
27 following which enrichment was added to pens and biters and/or victims were removed and
28 treated. 3D data from outbreak groups showed the proportion of low tail detections increased
29 pre-outbreak and declined post-outbreak. Pre-outbreak, the increase in low tails occurred at an
30 increasing rate over time, and the proportion of low tails was higher one week pre-outbreak (-1)
31 than 2 weeks pre-outbreak (-2). Within each batch, an outbreak and a non-outbreak control
32 group were identified. Outbreak groups had more 3D low tail detections in weeks -1, +1 and +2
33 than their matched controls. Comparing 3D tail posture and tail injury scoring data, a greater
34 proportion of low tails was associated with more injured pigs. Low tails might indicate more than
35 just tail biting as tail posture varied between groups and over time and the proportion of low tails
36 increased when pigs were moved to a new pen. Our findings demonstrate the potential for a 3D
37 machine vision system to automate tail posture detection and provide early warning of tail biting
38 on farm.

39

40

41 Introduction

42 Tail biting remains a persistent and unpredictable problem for pig producers worldwide impacting
43 on domestic pig (*Sus scrofa*) welfare and production [1-5]. Being tail bitten is painful [6] and
44 stressful [7] for pigs. Tail wounds can be a source of infection which spreads systemically [8]
45 resulting in further suffering from the resulting morbidity and mortality. In addition this leads to
46 partial or total carcass condemnation at slaughter resulting in losses of around €1.10 per pig
47 produced [9;10]. There are also negative impacts on pig growth estimated at €0.59 per pig [10]
48 and considerable on-farm labour and veterinary costs [4]. At slaughter, severe tail lesions (part or
49 total tail loss) affect 1-3 % of pigs [1;9] and detectable tail lesions affect over 70% of pigs [10]. On-
50 farm prevalence is very likely higher than abattoir estimates suggest [11;12].

51 Tail docking of piglets is widely used to mitigate the harms of tail biting and it does reduce tail
52 biting damage [11;13;14], but is not completely effective. Further, this mutilation is itself a
53 welfare concern [5;6;13], is seen as undesirable by consumers and its routine use is now banned
54 in the EU (by Council Directive 2008/120/EC). Tail biting can also be reduced (but not completely
55 prevented) by the use of loose material substrates such as straw or wood or by objects hanging in
56 the pen such as knotted ropes which occupy pigs' behavioural need to root and chew. However,
57 pigs find fresh or novel destructible materials most attractive [15;16] meaning that materials have
58 to be regularly replenished, which adds expense. Further, there is the technical difficulty that
59 many farms have slatted floors with liquid-slurry systems which cannot cope well with solid
60 materials [3].

61 Although access to substrates (limited by floor type) is important, several other environmental,
62 system and management factors including stocking density, pigs per stockworker, ammonia
63 levels, temperature, disease status, draughts, nutrition, season, competition for feed and
64 predictability of feed supply are thought to be risk factors for tail biting [1-4;17;18], and this lack

65 of a single clear cause makes the problem frustratingly hard to control. The specific trigger for any
66 given tail biting outbreak can vary and is usually unknown, and the uncertainty and
67 unpredictability that many farmers experience can be an important aspect of their motivation to
68 continue tail docking and to seek other solutions [19].

69 One approach which could reduce this unpredictability is to identify 'early warning signs' of tail
70 biting which could be used on farm to identify groups requiring intervention. Two recent reviews
71 have highlighted knowledge of behavioural changes that take place before an outbreak of
72 damaging tail biting [3;20]. These include: 1) Lowered tail posture- tails are held down rather than
73 up [21-25], 2) Increased activity and/or restlessness [22-24] but see [25], 3) Increased object-
74 directed behaviour [24] and 4) Increased tail biting behaviours: bites which are hard enough to
75 elicit a reaction from the victim [14;22]. These changes occur at the group level and there is also
76 evidence that certain individual pigs that will become tail biters or victims also show specific
77 changes [26].

78 In this study, we explore the potential of a 'precision livestock farming' approach to tail biting.
79 Precision livestock farming involves the use of modern sensor technologies to detect system,
80 environmental or animal-based indicators of growth, health, behaviour and welfare [27-30].

81 Sonoda et al [17] suggested that machine vision automated video- based systems could be used
82 in the detection of early warning signs for tail biting. The potential of 3D sensors in farm animal
83 behaviour measurement has been recently discussed [31]. Here we used 3D cameras, and
84 machine vision algorithms to automatically measure tail posture in pigs. Applying this technology
85 to groups of pigs before, during and after tail biting outbreaks, we explore its potential as an
86 automatic early warning system for tail biting.

87 Our specific aims were to: 1) Validate our 3D tail posture-detecting algorithm (3D tail posture) by
88 comparison with human observers' assessment of tail posture from video, 2) Establish whether

89 3D low tail posture increases prior to (and declines after) a tail biting outbreak, 3) Determine
90 whether 3D low tail posture is greater in outbreak than non-outbreak groups and 4) Establish
91 whether 3D low tail posture becomes more frequent with increasing tail injury as assessed by
92 regular clinical inspection of tails.

93 **Materials and Methods**

94 **Ethical considerations**

95 Tail biting is unpredictable, and in order to be certain of having some tail biting outbreaks to
96 study, we did not tail dock pigs and kept them in conditions in which tail biting was expected to
97 occur (i.e. at commercial stocking density in pens with fully slatted floors and limited enrichment).
98 This was considered to be a procedure likely to cause pain, distress or lasting harm under the
99 Animals Scientific Procedures Act (1986) and was regulated by the UK Home Office (Project
100 license number P3850A80D). Ethical approval was also obtained from SRUC's Animal Experiments
101 Committee (AE 27/2016), and (as a condition from BBSRC for their funding to SRUC) from NC3Rs
102 and BBSRC's Bioscience for Society Strategy Advisory (BSS) panel. Our primary aim was to collect
103 data on tail posture changes prior to tail biting outbreaks. Pigs were checked at least twice a day
104 by experienced stockworkers or technicians, and once an outbreak was detected, biters were
105 removed and injured pigs were given appropriate veterinary treatment, including analgesia,
106 topical and injected antibiotics, including long lasting antibiotics to reduce the risk of secondary
107 infection. Injured pigs were removed from the pen for recovery in hospital pens if necessary. Pigs
108 remaining in the pen were given enrichment (shredded paper, additional toys and chews –
109 wooden blocks, plastic balls). To prevent further outbreaks, the pen continued to be provided
110 with daily additional enrichment and other strategies were adopted in the event of renewed
111 outbreaks: swapping groups between pens, application of a tail tar (Kerbl Tar Paste, Albert Kerbl
112 GmbH, Germany) and/or provision of molasses blocks (PigLyx – Caltech Crystalyx, Cumbria, UK).

113

114 Before the project began, the herd size at the farm was reduced by 25% to free up pen space for
115 hospital pens, and additional deep-straw hospital pens were available and were used to aid
116 recovery in pigs which showed any signs of ill health (136/667 = 20.4% of pigs). Any pigs which
117 were thought to be suffering acutely or had failed to recover with treatment were humanely
118 euthanised by trained staff within one hour. Definition of these endpoints depended on the
119 nature of the ill health, but could include unwillingness to stand, lameness, lethargy and failure to
120 thrive. Euthanasia occurred in 27 cases, and in 12 cases pigs were found dead. This mortality level
121 of 39/667 (5.8%) between weaning and finish is slightly higher than the UK pig industry average
122 figure of 5.0% ([https://pork.ahdb.org.uk/prices-stats/costings-herd-performance/rearing-](https://pork.ahdb.org.uk/prices-stats/costings-herd-performance/rearing-finishing-7-110kg)
123 [finishing-7-110kg](https://pork.ahdb.org.uk/prices-stats/costings-herd-performance/rearing-finishing-7-110kg)), and probably reflects the higher level of monitoring, and a greater willingness
124 to euthanise pigs to reduce unnecessary suffering. All dead or euthanised pigs were sent for post-
125 mortem examination. Reasons for euthanasia / causes of death included nervous system disease
126 (1), intestinal problems including stasis, necrosis, torsion and bloat (6), heart problems (4), hernia
127 (5), various infections (7), lameness due to swollen joints or fracture (5), lung infections (3),
128 failure to grow and thrive (6) unknown cause (2). Post-mortem examination included
129 bacteriological sensitivity analysis to inform use of the most effective antibiotic for any further
130 cases of secondary infection. It was not possible to determine whether tail biting lesions
131 contributed to any of these deaths for example by being the route of infection. On one occasion
132 the post-mortem report identified tail biting as the suspected cause of intestinal stasis (in the
133 opinion of the post-mortem veterinarian), and 'tail bitten' was noted on two further reports. Our
134 legal and ethical duty of care for the health and welfare of pigs in this study continued beyond the
135 data collection period, and they were checked every day and treated if necessary until they were
136 sent for slaughter (mean \pm s.d. = 119.3 \pm 3.3 days after the study began at weaning). This included
137 regular veterinary checks and approval from a Named Veterinary Surgeon (as per Home Office
138 regulations) that the animals were fit for slaughter.

139 **Animals and housing**

140 The subjects of this study were 667 intact-tailed pigs (JSR Genetics Large White x Landrace x
141 Hampshire) of both sexes (entire males and females). They were the progeny of 55 sows, housed
142 in pens (2.38m long x 1.52m wide) equipped with standard farrowing crates (2.23m long x 0.47m
143 wide x 1.05m high). The crate had a solid floor with a slatted drainage panel at the back, which
144 was cleaned daily and the crate was replenished with fresh shredded paper and wood shavings. A
145 commercial lactation diet (ForFarmers NOVA; 15% Crude Protein, 13.75 MJ Digestible Energy kg⁻¹)
146 was offered twice daily at 0800h and 1500h and was increased from 1.5kg to approximately 6kg
147 per day according to litter size. The pens had a front creep area with heat lamp. Water was
148 available *ad libitum* for both sows and piglets. Piglets were offered a commercial creep diet
149 (Compound pellet creep feed, ForFarmers VIDA Maxima Piglet starter diet) from 7 days of age.
150 Commercial husbandry procedures performed on the piglets included a 1ml iron supplement
151 given intramuscularly at three days post-partum (Gleptosil, Alstoe Animal Health, York, UK) and
152 vaccination for Porcine Circovirus type 2 (Ingelvac CircoFLEX®, Boehringer Ingelheim, UK) at 21
153 days old.

154 Piglets were weaned into 23 groups of 29.0 ± 3.0 (mean \pm s.d.) at 35 days of age. At this point
155 groups were approximately balanced for sex ratio and average piglet weight. Phasing of farrowing
156 dates meant that there were eight contemporary batches of two or three groups at a time, and
157 data collection took place over a period of 7 months. There were two weaner pens per room,
158 each pen measured 2.5m x 2.5m (0.21-0.25m²/pig) and had fully-slatted plastic floors, was
159 equipped with a feeder (2.5m in length), nipple drinkers and basic forms of enrichment. This
160 included two flavoured round plastic enrichment devices (Porcichew, Ketchum, Epsom, UK)
161 suspended on chains. During this experiment additional enrichment was added after the first two
162 batches as tail biting outbreaks were occurring regularly. The enrichment included wooden blocks
163 and plastic balls hanging from the side of the pens. Pigs were given creep feed for the first 5 to 7

164 days before a commercial weaner-grower diet was mixed in (ForFarmers VIDA Ultima) and
165 provided *ad libitum*. Room temperature was maintained at 30°C for the first few days after
166 weaning before being gradually reduced to 24°C before the pigs were moved to grower
167 accommodation. Artificial lighting was operated on a 8h light:16h dark schedule, but the grower
168 rooms had natural ventilation which let in daylight.

169 Pigs remained in weaner pens for 26.7 ± 0.4 days, when they were moved in their same groups
170 into grower pens (two pens per room). Grower pens (3.20m width x 3.70 length; 0.40-0.47m² per
171 pig) had fully slatted concrete floors and were equipped with two feeders per pen (1.02m each in
172 length), nipple drinkers and two flavoured round plastic enrichment devices (Porcichew,
173 Ketchum, Epsom, UK) suspended on chains. Rooms were initially at 24°C reducing to 20°C seven
174 days after moving in and thereafter. Pigs were fed *ad libitum* with a commercial grower diet (For
175 Farmers HiGro). Pigs remained in grower pens for 25.4 ± 2.2 days at which point the data
176 collection part of the study ended with them being moved to finisher pens at 87.2 ± 2.1 days of
177 age (52.2 ± 2.1 days on the study).

178 **Tail injury scoring**

179 From weaning until the end of the grower period, pigs had their tails individually scored by a
180 person entering the pen and closely inspecting them. This was done three times a week, usually
181 on a Monday, Wednesday and Friday. Once a tail biting outbreak had occurred in a group (see
182 below), tail scoring was reduced to twice a week on a Monday and Friday. Four aspects of each
183 pig's tail were scored according to the scheme shown in Table 1: the severity of tail damage (0 to
184 4), wound freshness (0 to 5), length of tail missing (0 to 3) and the presence or absence of
185 swelling (0/1).

186

187 **Table 1 Tail injury scoring categories**

Category /Score	Short name	Description
Tail damage		
0	No tail damage	
1	Flattened	Tail is not round, appears flattened as though it has been sucked or chewed
2	Red	Tail appears red, or has red marks but no broken skin.
3	Puncture marks or scratches	Distinct scratches or puncture marks are visible, skin is broken
4	Wound	Raw flesh visible, tail has sustained tissue damage
Wound freshness		
0	No Wound	
1	Fresh bite or scratch	Not bleeding or weeping (for Damage Score 3 only)
2	Intact scab	
3	Broken scab	Older blood, red tissue
4	Fresh wound – not bleeding	Weeping or bloodied, blood stuck to tail hair
5	Fresh wound – bleeding	Blood dripping from tail wound, splattering the pigs' rump, pen walls or other pigs.
Tail length		
0	Full length tail	Still has the fluffy bit of hair on the tail tip
1	Shortened tail over half remains	Fleshy tail end, tail shortened, but more than half the tail still remains
2	Shortened tail less than half remains	Fleshy tail end, less than half the tail length remains
3	Tail stump	Less than 1 cm is left of the tail. The tail end is almost flush with the pig's rump
Swelling		
0	Tail not swollen	Tail has normal thickness
1	Tail swollen	Tail appears swollen: it is thicker than normal, creases in curves, pronounced or hacked

188 At each scoring event, each pig was scored for all four of these criteria. Modified after
 189 [11;25;32;33].

190 **Tail biting outbreaks**

191 Pigs were inspected at least twice daily with detailed observations during the morning checks. All
 192 pigs were checked for signs of tail damage, ill health or lameness with care to ensure all pigs were
 193 up and moving around during inspection. Occurrence of a tail biting outbreak was determined
 194 based on pen-side observations using only the information usually available to a farmer, and not
 195 the information available from our detailed tail scoring. A tail biting outbreak was considered to
 196 have occurred once any of the following three criteria was met: 1) when at least three pigs in a

197 pen have fresh tail wounds (see Table 1 - wound freshness score of four or higher) with visibility
198 from outside the pen, or 2) at least one pig with a currently bleeding wound (wound freshness
199 score five) which is obviously seen by dripping blood or splattering, or 3) where there is obvious
200 tail biting behaviour which is causing tail damage, not just 'manipulating tail' or 'tail in mouth'
201 behaviour [26;34].

202 If a tail biting outbreak occurred, protocols were immediately followed to stop the outbreak,
203 prevent further tail biting and safeguard the welfare of the pigs (See Ethical Considerations).

204 **3D data collection and processing**

205 Each weaner and grower pen had an IFM O3D301
206 (<https://www.ifm.com/gb/en/product/O3D301>) 3D camera orientated to cover around 1/3 of the
207 pen area, located above the feeder pointing vertically down. These cameras use time-of-flight
208 (ToF) technology which sends a pulse of infrared light from an LED 25 times a second, and then
209 records the delay between the pulse and its return to each pixel [31]. Ethernet data cables (Cat
210 5e) fed the data from each camera to an industrial fan-less PC ([http://www.fit-
211 pc.com/web/products/fit-pc4/](http://www.fit-pc.com/web/products/fit-pc4/)), connected to a broadband internet connection enabling data
212 download.

213 Proprietary algorithms produced by Innovent Technology Ltd were used to locate pigs and orient
214 them. For each pig that was present under the camera and standing up, a further algorithm was
215 used to locate the tail and measure its angle relative to the body on a scale of 0 to 90 degrees,
216 where 0 is a tail which is hanging down or tucked against the body so it does not stand out from
217 the curve of the back/rump, and 90 is a tail standing up at 90 degrees. The 3D camera recorded
218 continuously 24 hours a day, and detected tails as often as the system was able. The number of
219 detections is reported in the results. Tail detections cannot be assigned to individual pigs. The
220 system functioned at the group level.

221 To collate these raw tail angle data into a daily summary of tail posture for each pen, tail angle
222 data were converted into a tail posture score between 0 and 3, where $0^\circ = 0$ (low tails), $>0^\circ$ to 30°
223 $= 1$ (part-raised tails), $>30^\circ$ to $60^\circ = 2$ (raised tails) and $>60^\circ$ to $90^\circ = 3$ (high tails; referred to
224 subsequently here as 3D 0, 3D 1, 3D 2 and 3D 3). The number of detections in each category were
225 counted, and converted into a proportion of total 3D data for that group and day. Days with
226 fewer than 100 detections were discarded from subsequent analysis, as we considered that data
227 were too sparse to reliably record the overall group level proportion of tail postures.

228 **2D video data collection**

229 Each pen was equipped with two 2D video cameras (“Gamet Professional” Sony effio bullet CCTV
230 camera (Gamut, Open 24 seven Ltd, Bristol, UK)); mounted in the ceiling; one capturing the entire
231 pen and one capturing above the feeding area where the 3D camera was also positioned. The two
232 cameras recorded continuously 24 hours per day and video data were stored on the hard drive of
233 a PC-based CCTV system (GeoVision software (GeoVision UK, Letchworth, Herts, UK)).

234 **3D data validation by comparison with 2D video**

235 3D and 2D video images were watched simultaneously to validate 3D data ‘by eye’. Three
236 observers viewed data from five, seven and eight groups respectively, selected at random. Data
237 were sampled at intervals between 0800 – 1600h, to obtain between five and 10 observations per
238 hour, on day -1 pre-outbreak (or the same day in matched control pair groups). Where data were
239 missing for technical reasons, the next available frames were used. If data were not available on
240 day -1 outbreak then days -2 and -3 were used. This resulted in a mean (\pm s.d.) of 45.5 (\pm 15.5)
241 samples per observer/group, or 911 in total.

242 For these human observer recordings, tail position was classified as curled, high loose, low loose
243 or tucked down against the body. Curled was defined as a visible loop in the tail, where two parts

244 of the tail overlap, regardless of tail angle. High loose was a non-curved tail that hung at least 45
245 degrees from the vertical plane of the body. Low loose was a non-curved tail that hung between 0
246 and 45 degrees from the vertical plane of the body. Tucked was a non-curved tail that was held
247 inwards towards the body. To ensure consistency, the three observers discussed and agreed
248 these classifications before starting. The results of different observers showed agreement over
249 the proportion of pigs in each tail category at a mean (\pm s.d.) level of $75.2 \pm 16.5\%$.

250 **Statistical Methods**

251 Microsoft Excel was used for organising and summarising data and Genstat 16.1 (VSN
252 International Ltd) was used for analysis. After model fitting, inspection of residual plots was used
253 to confirm the assumptions of normal distribution and heterogeneity of variance without
254 transformation.

255 To compare injury scoring data (proportion of pigs with 0 damage score) over time between
256 outbreak and contemporary 'control' groups with no outbreak, one outbreak and one non-
257 outbreak (control) group were selected from within each batch, based on the amount of 3D data
258 available in the 2 weeks pre-outbreak. The non-outbreak groups' days were numbered relative to
259 the outbreak of the group they had been paired with. Weeks were coded as -2 (days -14 to -8), -1
260 (days -7 to -1), +1 (days 0 to 6) and +2 (days 7 to 13). Linear Mixed Models (using REML) were
261 fitted in Genstat. The random model was Batch/Group/Day, and the Fixed model was Week,
262 Outbreak vs Control and their interaction.

263 Validation of 3D data against human observers' assessments was analysed using a chi-squared
264 test for association, comparing human observers' scoring of tucked or not tucked against the
265 algorithm data: 3D 0 or not 3D 0 (3D 1, 2 and 3). Following this validation, it was decided that 3D
266 0 'low tails' was accurate enough to use in further analysis, but that the other 3D classifications
267 were not.

268 For 3D tail posture data, all analyses were run using the proportion of detections that day which
269 were 3D 0 'low tails' as the response variate. To begin with, the outbreak groups were analysed to
270 look at changes over time relative to the outbreak day. First, all available pre- and post-outbreak
271 data were analysed, fitting a polynomial regression model with a single curved line for all the
272 data, and then by fitting a line for each group. Second, all available pre- outbreak data were
273 analysed fitting a polynomial regression, followed by fitting a line for each group. Lastly, the
274 effect of week (-2 or -1) on the proportion of 3D 0 low tails for the 14 days prior to an outbreak
275 was tested using ANOVA with Group/Day as the blocking structure. Only 10 of the 16 outbreak
276 groups were included in this analysis as these had at least 2 days of data from each week (week -
277 1, mean \pm s.d. = 5.5 ± 2.0 days of data; week -2, 6.3 ± 1.6 days of data; 118 days included in
278 analysis). As well as ANOVA, regression models were also fitted to these data from days -14 to -1.
279 Then, 3D 0 data were compared between outbreak and contemporary 'control' groups with no
280 outbreak for the 2 weeks before and after an outbreak, using a mixed model as described above
281 for injury scoring data.

282 Finally, to determine the relationship between 3D and injury scoring data, a series of Linear Mixed
283 Models were fitted to all of the tail injury scoring data (as the response variable), with separate
284 models with tails low (3D 0) as the explanatory variable (Fixed model). These models always
285 included a random term of batch/group/date.

286 **Results**

287 **Tail biting outbreaks**

288 There were 15 tail biting outbreaks in the 23 groups (65.2%), occurring between 16 and 41 days
289 (mean \pm s.d. = 28.2 ± 9.3) after weaning. Five outbreaks occurred in the weaner pens and 10 in
290 grower pens.

291 Tail injury scores over time

292 In total, 12,440 tail injury scores were recorded. For outbreak groups only, the average tail injury
293 score (damage) by week relative to outbreak are shown in Fig 1 and tail injury scores for tail injury
294 freshness, tail length and tail swelling are shown in S1 Fig. Damage and freshness scores began to
295 increase in the weeks prior to an outbreak, while swelling and tail length increased only just
296 before, or after an outbreak. The average proportion of pigs with damage score 0 in non-outbreak
297 groups remained at around 0.6 – 0.7 over the 2 weeks before and after an outbreak (Week-2 =
298 0.677 ± 0.064 ; -1 = 0.663 ± 0.061 ; +1 = 0.7099 ± 0.0671 ; +2 = 0.5929 ± 0.0693), while this
299 proportion fell markedly in outbreak groups (Week-2 = 0.556 ± 0.0616 ; -1 = 0.375 ± 0.061 ; +1 =
300 0.198 ± 0.0627 ; +2 = 0.2065 ± 0.0682). A linear mixed model revealed a significant effect of
301 treatment ($F_{1,7} = 24.98$, $p = 0.002$), week ($F_{3,50} = 9.53$; $p < 0.001$) and a significant interaction
302 between these ($F_{3,50} = 8.01$, $p < 0.001$). LSD tests showed that the difference between control and
303 treatment was significant at $p < 0.05$ for all weeks except Week -2. Tail injury data for control
304 groups are shown in S2 Fig.

305 **Fig 1. Mean proportion of pigs from the 15 outbreak groups with different tail injury scores (tail**
306 **damage) in the weeks before and after an outbreak.** 0 No damage, 1 Flattened, 2 Red, 3 Bite
307 marks or scratches, 4 Wound

308 3D data collected

309 1200 days of data (23 groups \times mean of 52.2 days) were expected, but due to various technical
310 difficulties, only 962 days were successfully collected, and of these 827 were used for analysis
311 (135 days with fewer than 100 tail detections were discarded from the analysis). In total,
312 2,152,101 3D tail angle measurements were obtained using the machine vision algorithm, but the
313 number per day was very variable. The greatest number in a day was 20,371, and the mean (\pm
314 s.d.) was 2237 (± 2746).

315 Of those tail detections, tail angle was measured at 0° 58.2% of the time (3D 0; 1,251,601
316 detections), indicating that the tail was hanging too low to be detected relative to the curve of
317 the back. It fell between >0° and 30° 19.3% of the time (3D 1; 416,250 detections), between >30
318 and 60° 14.9 % of the time (3D 2; 321,552 detections) and between >60° and 90° 7.6 % of the
319 time (3D 3, 162,698 detections).

320 **3D data validation against 2D video**

321 Data from the three observers were similar so they were combined for analysis. In total there
322 were 926 visual validations of the 3D algorithm against 2D video images (Fig 2). The algorithm
323 was good at identifying tails which were tucked low against the body (and quite good at
324 identifying low hanging tails). Tails which were visually identified as tucked (302) were accurately
325 identified by the algorithm as being low (3D 0) 88.4% of the time (267/302 true positive rate;
326 sensitivity). Tails which were visually identified as not being tucked (624) were accurately
327 identified as not being low (3D 1, 2 or 3) 66.8% of the time (417/624 true negative rate;
328 specificity). A chi-squared test on this data showed a significant association between tucked and
329 3D 0 ($\chi^2 = 248.5$, $p < 0.001$). Thus the overall accuracy of the algorithm (correct classifications 684
330 / total 926) was 73.9%. For hanging low tails, 53.4% (71/133) were classified as 3D 0 by the
331 algorithm. If visual identifications of tucked and hanging low tails are combined and the algorithm
332 is considered correct if it classifies these as 3D 0, then the sensitivity is 77.7%, specificity is 72.3%
333 and accuracy is 74.8%. Of the 474 3D 0 'low tail' observations, these indicated a tucked or low
334 loose tail 71.3% of the time.

335 Hanging high was correctly identified (as 3D2 or 3D3) 56.2% of the time (50/89). Curly tails were
336 not handled very well by the algorithm despite being quite commonly observed (386/926 = 41.7%
337 of visual checks), being classified fairly evenly across all of the 3D detection categories (Fig 2).

338

339 **Fig 2. Bar graphs of 3D data validation by a human observer.** 926 automatic 3D tail detections
340 were checked by eye and described as curled, high loose, low loose or tucked ('short tails up'
341 occurred only 16 times so data are not shown). Data are grouped by the visual observation
342 categories, using different colours for the 3D tail categories. Note that $0^\circ = 3D\ 0$ (low tails), $> 0^\circ$
343 to $30^\circ = 3D\ 1$ (part-raised tails), $> 30^\circ$ to $60^\circ = 3D\ 2$ (raised tails) and $> 60^\circ$ to $90^\circ = 3D\ 3$ (high tails).
344 Numbers on the bars show the frequencies.

345

346 **3D low tails in outbreak groups pre- and post- outbreak**

347 For the 15 outbreak groups, 3D 0 'low tails' daily proportions were plotted relative to the
348 outbreak day (Fig 3). There were between 25 and 51 (mean \pm s.d. = 41.93 ± 7.95) days of data
349 available for each group. A simple polynomial regression model fitted to this data was significant
350 ($F_{2,543} = 101.33$, $p < 0.001$; $R^2 = 26.9$; Table 2). Linear and Quadratic terms were both significant
351 (Linear term estimate 33.2×10^4 , $p < 0.001$; Quadratic term estimate -2.5×10^4 , $p < 0.001$). A
352 positive linear term indicates that 3D 0 (low tails) increased over time, while a negative quadratic
353 term indicates that the data are curving down (in an inverted U shape; Fig 3), reflecting an
354 increasing proportion of low tails as an outbreak approaches, followed by a decline in low tails
355 after an outbreak, once various mitigation measures are put in place to reduce tail biting.

356 A second type of regression model was also fitted, in which separate lines were fitted for each
357 group. This was also significant ($F_{44,501} = 42.97$, $p < 0.001$) and fitted the data much better ($R^2 =$
358 77.2). Of the 15 groups, 13 had a significant ($p < 0.05$) linear coefficient. Of these, nine were
359 positive indicating an increase in 3D 0 (low tails) over time, and four were negative. Eleven groups
360 had a significant ($p < 0.05$) quadratic term. Of these, 10 had negative quadratic coefficients,
361 indicating that the relationship between 3D 0 (low tails) and time takes an inverse-U shape (Fig 3).
362 One group had a positive quadratic term indicating a U shape.

363 **Fig 3. Proportion of 3D tail detections of low tails (3D 0) on the days before and after an**
364 **outbreak.** Data are shown for the 15 outbreak groups, and each line indicates a different group
365 (designated Alpha to Victor).

366

367 **3D low tails in outbreak groups pre- outbreak**

368 For the 15 outbreak groups, regression models of the proportion of pigs in the pen with low tail
369 posture (3D 0) on each day, against day were fitted to the pre-outbreak data (data used for this
370 analysis are shown in Fig 3 to the left of the y axis). In this analysis, there were between 1 and 37
371 days of data available for each group (mean \pm s.d. = 20.87 ± 9.87). A simple polynomial regression
372 model fitted to this data was significant ($F_{2,243} = 54.3$, $p < 0.001$; $R^2 = 30.3$). A positive linear term
373 (193.3×10^4 , $p < 0.001$) indicates that the proportion of low tail pigs increased over days pre-
374 outbreak, and a positive quadratic coefficient (3.6×10^4 , $p < 0.001$) shows that this occurred at an
375 increasing rate. A model fitting a separate line for each group, provided a better overall fit ($F_{41,204}$
376 = 32.4 , $p < 0.001$; $R^2 = 84.0$), eight of these lines had significant positive linear coefficients (six
377 were not significant), and eight had significant positive quadratic coefficients.

378 **3D low tails in outbreak groups comparing one week and two** 379 **weeks pre- outbreak**

380 For the 10 outbreak groups with sufficient data for this analysis (at least 2 days of data in week -2
381 and week -1), the proportion of pigs with low tails (3D 0) was higher in week -1 (0.562 ± 0.009)
382 than in week-2 (0.473 ± 0.009 , $F_{1,107} = 47.5$, $p < 0.001$; Fig 4). This was supported by a significant
383 regression analysis of the same data ($F_{1,107} = 67.6$, $p < 0.001$). The positive regression coefficient
384 (0.013 ± 0.002) indicates that the proportion of low tails increased over the 14 days prior to an

385 outbreak. A polynomial regression was also fitted to these data, but the quadratic term was not
386 significant.

387

388 **Fig 4. Proportion of 3D low tail detections (3D 0) on the days leading up to an outbreak.** Data
389 are shown for the 10 outbreak groups for which there were at least 2 days of data between days -
390 1 and day-7 (week -1) and also 2 days of data between days -8 and -14 (week - 2). Each line
391 shows data for a different group.

392

393 **3D low tails compared between outbreak and control groups**

394 The proportion of low tails (3D 0) for each outbreak vs. control pairing for the 8 batches are
395 shown in S3 Fig. Where data are available, the post-outbreak differences are always clear, and in
396 many cases, outbreak groups appear higher than controls in the days pre-outbreak. The day that
397 pigs were moved from weaner to grower accommodation is also indicated in S3 Fig, and it often
398 appears that this change of pen resulted in an increase in low tails in both control and outbreak
399 groups. Based on this observation, the growth stage was included in analysis of these data.
400 Another notable feature of these graphs is that there are large differences between groups in the
401 baseline proportion of low tails (3D 0).

402 A Linear Mixed Model was used to compare outbreak and control groups over weeks -2,-1,+1 and
403 +2 relative to outbreak within each batch. After adjusting for a highly significant effect of growth
404 stage (mean \pm s.e. Weaner = 0.53 ± 0.09 , Grower = 0.63 ± 0.09 ; $F_{1,215} = 126.5$, $p < 0.001$), the
405 Outbreak pigs showed a higher proportion of low tails than Control pigs ($F_{1,5} = 7.47$, $p = 0.046$; Fig
406 5). Least significant difference tests showed significant differences in low tails between outbreak
407 and control pigs at $p < 0.05$ during weeks -1, +1 and +2. There was a significant time*treatment

408 interaction ($F_{3,93} = 29.5$, $p < 0.001$), low tails increased over time in outbreak but not control
409 groups.

410 **Fig 5 Estimated means (\pm s.e.) for the proportion of 3D low tail detections (3D 0) during the 2**
411 **weeks before and the 2 weeks after a tail biting outbreak.** Week -2 was days -14 to -8, week -1
412 was days -7 to -1, week +1 was days 0 to 6 and week +2 was days 7 to 13. Data were from one
413 outbreak and one control (non-outbreak) group from each of the 8 batches. For control groups,
414 the weeks were assigned by using the outbreak day of their contemporary outbreak group from
415 the same batch. Estimated means were generated from a Linear Mixed Model of Growth Stage
416 (weaner or grower) + Week + Outbreak Vs Control + Week*Outbreak Vs Control, with
417 Batch/Group/Day as the random effects. The * indicates a significant ($p < 0.05$) difference between
418 Outbreak (indicated by red squares) and Control groups (blue diamonds) at the indicated time
419 point (based on Least Significant Difference testing).

420 **3D low tails as a predictor of injury scores**

421 Linear Mixed Models were used to determine the overall relationship between 3D tail posture
422 and tail injury across all groups (including outbreak and control) and days. The negative
423 coefficients of effect in Table 2 show that when there are fewer low tails (3D 0) there are many
424 pigs with uninjured tails (Damage 0, Fresh 0, Swelling 0) or slightly injured tails (Damage 1 or 2). In
425 contrast, positive coefficients of effect in Table 2 indicate that more low tails (3D 0) were
426 predictive of a greater proportion of damaged tails (Damage score 3 or 4), freshly injured tails
427 (Freshness score 1,4 or 5) or reduced tail length (Length 1).

428

429 **Table 2. Relationship between tail damage scores and 3D low tails data.** Data shown are the
 430 coefficient of effect (\pm standard error) for a series of Linear Mixed Models using the proportion of
 431 pigs with the various tail injury scores as the response, and proportion of 3D 0 low tails as the
 432 predictor (fitting batch/group/date as the random effect model). Data for all groups and all days
 433 were used in these models. Asterisks are used to indicate the level of significance, * $p < 0.05$,
 434 *** $p < 0.001$. NS indicates that there was no significant relationship.

435

Proportion of pigs with Tail Injury Score	3D 0 Low tails
Damage 0	-0.703 \pm 0.094***
Damage 1	-0.083 \pm 0.032*
Damage 2	-0.210 \pm 0.034***
Damage 3	0.100 \pm 0.040*
Damage 4	0.831 \pm 0.097***
Fresh 0	-1.033 \pm 0.082***
Fresh 1,4 or 5	0.400 \pm 0.048***
Length 0	NS
Length 1	0.158 \pm 0.073*
Swelling 0	-0.197 \pm 0.024***

436

437 Discussion

438 Tail biting is to some degree unpredictable making it difficult to study [3], but the risk factors are
 439 known. We were able to induce tail biting in 65% of groups, by keeping pigs with intact tails on
 440 slatted floors with minimal enrichment. The timing of outbreaks still remained variable and
 441 unpredictable.

442 Our first aim was to validate the 3D tail posture-detecting algorithm against human observers'
443 visual assessment of tail posture. The algorithm performance was not perfect, and there is clearly
444 room for improvement for the most commonly seen category of tail posture - curly tails, as the
445 algorithm allocated these fairly evenly across the 3D tail categories. The algorithm did best with
446 tucked tails, correctly allocating them as 3D 0 low tails 88.4% of the time. It also did fairly well
447 with low loose tails, allocating them as 3D 0 low tails 53.4% of the time. We took the decision that
448 only 3D 0 was reliable enough for further analysis, as this metric indicated a tucked or low loose
449 tail 71.3% of the time, and 58% of all tail detections were low (3D 0). Given the difficulty that the
450 algorithm was having with curly tails, it would be interesting to test it in future with tail-docked
451 pigs which are unable to curl their tails.

452 Our second aim was to establish whether automatically detected (3D 0) low tail posture changed
453 prior to a tail biting outbreak. Regression analysis showed that the proportion of low tails
454 increased pre-outbreak, and at an increasing rate, declining again after an outbreak. When the
455 two weeks pre-outbreak were compared, there was evidence of an increase in low tails from
456 week -2 to week -1, and over the 14 days. These results provide support for the suggestion that
457 low tail posture does increase pre-outbreak as reported by other authors [21-25] and could be
458 used as an (automated) early warning sign of outbreaks.

459 Our third aim was to compare 3D tail posture data in outbreak and contemporary non-outbreak
460 (control) groups. For a week pre-outbreak (week -1), and post-outbreak (weeks +1 and +2), low
461 tails were higher in outbreak groups than controls, even after the effect of growth stage was
462 taken into account. This provides further support for the idea of using this technology as an early
463 warning sign of tail biting. These outbreak vs. control differences in low tail posture occurred
464 despite the fact that our control groups were not completely free from tail injury. A method to
465 increase contrast in the degree of tail injury between outbreak and control groups would have
466 been to use high levels of enrichment to reduce tail biting risk for control groups. However, this

467 environmental change might itself have influenced tail posture leading to a confound, and the
468 unpredictability of tail biting and variability between groups may still have resulted in some tail
469 damage and tail biting outbreaks in enriched control pens.

470 Our fourth aim was to establish whether there was a general relationship between 3D tail posture
471 data and tail injury scores across groups and time points. This analysis ignored the distinction
472 between outbreak and control groups. A series of linear mixed models showed that there were
473 significant relationships: when there were many uninjured pigs, or lightly injured pigs in the
474 group, there were fewer low tail posture detections (3D 0). Greater proportions of low tails were
475 seen when injured pigs were more common in the group. The inverse-U shape of the graph in Fig
476 3 also reflects this increase in low tails as an outbreak draws closer and the decline in low tails
477 after an outbreak when steps are taken to stop further tail biting so tails can recover.

478 Some authors [22-24] have found increased activity before tail biting outbreaks [but see 25], so
479 activity has potential as an early warning sign. In principle, the number of 3D tail detections per
480 day could be used as a proxy for activity, since pigs must be standing up under the camera to be
481 detected, but the large variability in detections per day meant that we did not try to analyse this.
482 There are various possible reasons for variability in the number of detections. All cameras were
483 connected to a single PC, so the system may have been stretched to capture data from all pens at
484 once. The number of pens under the cameras which had pigs in could vary. There may have been
485 variation in pig behaviour over days in the amount of tail movements such as tail wagging which
486 may have reduced successful tail detections [35]. Some refinements were made to data capture
487 and the algorithm for tail posture detection over the course of the project, which appeared to
488 result in a reduction in missing data and an increase in detections in later batches, but the
489 number of detections per day still remained variable.

490 In this study, our aim was to identify early indicators of tail biting which were early relative to the
491 stage at which a farmer would usually recognise tail biting and take action. Our criteria for an

492 outbreak (recognised from outside of the pen) was of three pigs with fresh wounds, or one or
493 more pigs with bleeding tails, or obvious tail biting behaviour causing damage. Our tail scoring
494 data (based on closely observing tails from within the pen) showed gradually increasing signs of
495 tail damage at least 1-2 weeks before this point (Fig 1, S1 Fig). Other authors who have worked in
496 this area used different definitions of an outbreak. Zonderland et al [23] analysed data at an
497 individual pig level, and showed that a pig's tail was more likely to be held tucked between the
498 legs during the transition from no damage to pinhole bite marks, as well as during transitions
499 from uninjured or bite marked tails to clear tail wounds. Lahrman et al [25] used a definition of 4
500 pigs in a pen (of ~30 pigs per pen) having a wound, which could include healing or scabbed
501 wounds. If we had used this definition, it would likely have resulted in calling an outbreak in some
502 pens sooner than we did with our method. The concept of an 'early' indicator is clearly relative to
503 the definition used for an outbreak of tail biting. The fact that tail injuries are evident through
504 careful tail scoring well before tail biting outbreaks becoming obvious from outside the pen
505 suggests that if an automated method of detecting tail injuries could be developed (e.g. tail
506 colour or tail temperature), this could also give early warning of outbreaks, perhaps in
507 combination with tail posture.

508 There was considerable variability in the baseline level of the proportion of low tail detections (3D
509 0) between groups (Figs 3 and 4, S3 Fig), which was also reflected in the much improved
510 regression model fit when lines for each group were fitted. Thus, a method of predicting tail
511 biting from 3D data which depends on detecting a deviation from each groups' baseline is likely to
512 be the best approach for detecting tail biting. Inspection of S3 Fig suggests that on occasion,
513 trends in tail posture over time co-vary between contemporary groups, probably independently
514 of tail biting. In particular, the proportion of low tails (3D 0) often increases markedly at the same
515 time in both the control and outbreak groups of a contemporary pair when they are moved to a
516 new pen. There is clearly a lot more that we are yet to find out about what affects this
517 'background' tail posture, which would be useful to know for further refinement of an early

518 warning system. For example, it is possible that tail posture could be a general indicator of the
519 state of arousal or of emotional state in pigs [35;36], meaning that it could be altered by other
520 physical or social stressors, or disease status rather than being only an indicator of early tail
521 biting. An additional concern is that the multifactorial nature of tail biting risk-factors most likely
522 means that some types of outbreak may be more amenable to early detection than others. If an
523 outbreak was triggered by the stress caused by a drinker, feeder, ventilation or heating failure,
524 this could occur relatively rapidly.

525 The changes in tail posture and tail injury pre-outbreak in our study were similar to those found
526 by other authors [21-25]. Even in the absence of high-tech approaches, these changes, along with
527 signs of tail injury, could be used as advance warning of tail biting outbreaks by farmers with
528 sufficient time to inspect their pigs closely and often enough. Increased awareness and use of
529 early warning signs could reduce the unpredictability of tail biting, giving pig producers greater
530 confidence to cease tail docking in compliance with the requirements of EU council directive
531 2008/120/EC to use tail docking as 'a last resort'.

532 Our findings provide 'proof of concept' for the idea that using 3D video cameras to record tail
533 posture could be developed into an early warning system for tail biting outbreaks. Whether this
534 can be applied in commercial farming will depend on whether a real time predictive system can
535 be successfully designed and on the economic cost vs. benefits of such a system. The cost of 3D
536 cameras is relatively high, but their use would be more economically viable if tail biting prediction
537 were only one aspect of a multifunctional system used to detect other commercially important
538 traits such as pig growth [37], aggressive behaviour [38], or behavioural indicators of ill health
539 [29;39].

540 In conclusion, our results show for the first time that using Time-of-flight 3D cameras and
541 machine vision algorithms to detect low tail posture have the potential to provide an automatic
542 early warning sign for tail biting. The tail-posture detection algorithm was accurate enough; the

543 proportion of low tails increased over time pre-outbreak, was greater in outbreak groups than
544 control groups, and was associated with increased tail injury. Our study contributes to the rapidly-
545 growing area of 'precision livestock farming', using new technologies to inform farm management
546 decisions by providing real-time information on animal growth, health, behaviour and welfare
547 [27-31].

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- 657

658 **Supporting information**

659 **S1 Fig. Mean proportion of pigs from the 15 outbreak groups with different injury scores in the**
660 **weeks before and after an outbreak.** a) Freshness scores (0 No wound, 23 Scab, 145 Fresh), b)
661 Tail length (0 Full length, 1 Shortened, 2 More than half missing, 3 Stump), c) Tail swelling (0 Not
662 swollen, 1 Swollen). Note that Damage scores are shown in Fig 1.

663 **S2 Fig. Mean proportion of pigs from the 8 control groups with different injury scores in the**
664 **weeks before and after an outbreak in their matched-pair within batch outbreak group.** a)
665 Damage scores (0 No damage, 1 Flattened, 2 Red, 3 Bite marks or scratches, 4 Wound), b)
666 Freshness scores (0 No wound, 23 Scab, 145 Fresh), c) Tail length (0 Full length, 1 Shortened, 2
667 More than half missing, 3 Stump), d) Tail swelling (0 Not swollen, 1 Swollen).

668 **S3 Fig. Graphs of proportion of low tails (3D 0) over days relative to outbreak for outbreak and**
669 **control groups within each batch, graphs a) – h) show data for batches 1-8 respectively.** The x
670 axis shows days relative to the outbreak for the outbreak group, and the same (calendar) day for
671 the corresponding control group. Outbreak data are indicated by a blue line with diamonds and
672 control data by a red line with squares. The black triangle on the x axis indicates the day on which
673 the pigs were moved from weaner to grower accommodation.

674 **S1 Dataset. 3D vs. tail scoring main data**

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