Veterinarni Medicina, 64, 2019 (11): 497–504 *Original Paper*

https://doi.org/10.17221/13/2019-VETMED

The loading characteristics of landing in cats with different body weights

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Citation: Song Y, Wang M, Baker JS, Gu Y (2019): The loading characteristics of landing in cats with different body weights. Veterinarni Medicina 64, 497–504.

Abstract: Nowadays, quadrupedal locomotion information is well established for dogs, horses, and pigs, and kinetic systems have been widely used for sensitive and reliable gait analysis. However, few studies have investigated cat locomotion and the data available are confusing and restricted, especially in relation to jumping. In addition, it has been suggested that several factors, including the influence of the body weight (BW), may be associated with the collection of the kinetic data measurements in dogs. This raises the question of whether the BW would influence the kinetic data measurements in cats. Therefore, this study was aimed at comparing the kinetic parameters of the landing during the jumping in cats with different BWs and to determine the associations between the BW and the kinetic parameters. Twelve client-owned cats were sub-divided into two groups based on the BW and were categorised as a thin group and a heavy group. Each cat was encouraged to jump from a table (1.0 m) onto a force plate several times. The trials were considered to be valid if the cat jumped normally onto the plate and then continued to walk forward. The kinetic parameters including the peak vertical force (PVF) and the vertical impulse (VI) were obtained for each limb. In addition, correlations between the PVF, VI, and BW and the symmetry index (SI) of the forelimbs and hindlimbs were also determined. Most of the kinetic parameters of the thin cats were significantly smaller than the heavy cats during the landing and these values increased as the BW increased, while the normalised PVF and VI of the forelimbs were significantly smaller in the heavy cats than in the thin cats. In addition, for both groups, the non-normalised or normalised PVF and VI were significantly larger in the forelimbs than the hindlimbs, and the SI of the PVF was significantly smaller at the forelimbs than in the hindlimbs. In conclusion, the results of this study showed substantial similarities and differences during the landing between thin and heavy cats. These findings should provide more reference data for the biomechanical motion analysis related to jumping in clinically intact cats.

Keywords: biomechanics; motion analysis; kinetic data; forelimbs; hindlimbs; peak vertical force; vertical impulse; symmetry index

The biomechanical motion analysis in quadrupeds, such as dogs, horses, and pigs, has been an essential part of veterinary orthopaedic studies for many years (Schnabl and Bockstahler 2015; Schnabl-Feichter et al. 2017). However, it is surprising to find that very little information regarding feline biomechanical motion analysis has been established and reported. In addition, among the few reports on felines (Lascelles et al. 2007; Lequang et al. 2010; Verdugo et al. 2013; Corbee et al. 2014; Stadig and Bergh 2015; Schnabl-Feichter et al. 2017), most of the studies have investigated the normal gait during walking, and little biomechanical analysis has been conducted

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Supported by the National Natural Science Foundation of China under Grant (No. 81772423), NSFC-RSE Joint Research Programme (No. 8181101592), and K. C. Wong Magna Fund in Ningbo University.

to study the jumping ability. This is in spite of cats being able to perform this movement extremely efficiently. It is well recognised that cats have always been used as experimental models to investigate the neural control of motion, or the regenerative possibilities of spinal cord injuries in humans (Abraham and Loeb 1985; Abraham et al. 1985; Barbeau and Rossignol 1987; Pratt and Loeb 1991; Loeb 1993; Bouyer and Rossignol 2003). Therefore, more information on feline biomechanical motion analysis related to jumping would not only enhance our understanding of feline locomotion, but also provide more data for human locomotion research.

Various biomechanical motion analysis methods have been used to explore quadrupedal locomotion, with kinetic gait analysis being the most common (Schnabl and Bockstahler 2015). Kinetic analysis can provide information about the ground reaction forces produced by the contact between the limbs and the ground, which inform on, predict and assess gait disabilities (McLaughlin 2001; Verdugo et al. 2013; Schnabl and Bockstahler 2015). The most frequently evaluated parameters included in the orthogonal vertical ground forces are the peak vertical force (PVF) and the vertical impulse (VI) (Schnabl and Bockstahler 2015). Moreover, symmetry is often used as an indicator of gait dysfunction to detect limb lameness during walking and trotting in dogs (Voss et al. 2007; Kim et al. 2011) and cats (Verdugo et al. 2013; Schnabl-Feichter et al. 2017). However, the symmetry of landing after jumping in cats remains unclear and requires further exploration.

Among these studies on quadruped species, various systems have been used to analyse the gait, including high-speed cameras (Gillette and Angle 2008), pressure-sensitive walkways (Verdugo et al. 2013), and force plates (Corbee et al. 2014). The use of pressure-sensitive measurement systems has gained increased popularity, as these systems may have some unique advantages over other systems (Meijer et al. 2014; Stadig and Bergh 2015; Fahie et al. 2018). Force plates have been considered as the "gold standard" to measure the ground reaction force for years (Voss et al. 2011; Fischer et al. 2013). Using force plates to analyse the gait in cats has not been used regularly, this is also true for studies relating to the jumping ability. Therefore, there is a need to use force plates to objectify and analyse the jumping capability in this species.

In addition, less information is available on the influence of the body weight (BW) on the kinetic parameters during the normal jumping in cats. However, in domestic dogs, it has been suggested that the BW may be associated with the kinetic data measurements (Budsberg et al. 1987; Kim et al. 2011). For example, Budsberg et al. (1987) evaluated the ground reaction forces and associated impulse distributions in healthy, medium to large dogs and they found that the PVF increased as the BW increased. This finding raises the question of whether BW would influence the kinetic data measurements in cats. Therefore, the purposes of this study were to compare the kinetic variables of landing during the jumping in cats with different BWs, using a force plate, and to determine any associations between the BW and kinetic parameters. It was hypothesised that the thin cats would have different kinetic gait patterns during the landing from the heavy cats, and that the BW would be associated with the magnitude of the measured kinetic parameters.

MATERIAL AND METHODS

Animals. Twelve clinically intact cats recruited from client-owned individuals were included in the study. All the cats were judged to be clinically intact according to a full physical examination performed by the same veterinarian. The body weight (BW) of each cat was determined using an electronic weighing scale. The cats were then divided into two groups based on the BW; a thin group (SG: < 3 kg; mean BW, 2.7 kg; $n = 6$) and a heavy group (LG: > 5 kg; mean BW, 5.4 kg; $n = 6$). An informed owner consent was obtained prior to the testing and the experimental procedures were approved by the Animal Care and Use Ethics Committee at Ningbo University.

Experiment equipment. The kinetic data during the landing was recorded using an emed®-m pedography force plate platform (Novel GmbH, Munich, Germany). The force plate had an active sensor surface of 0.395 m × 0.24 m containing 3792 sensors (4 sensors per cm^2), with a measuring frequency of 50 Hz. The force plate was connected to a computer and the obtained kinetic data were analysed using the specialised software (Novel database essential; Novel GmbH, Munich, Germany) provided by the manufacturer. Prior to the data acquisition, the calibration of the force plate was performed following the manufacturer's instructions.

Experiment protocols. This test was conducted in a quiet room with only the researchers and the owner(s) present. Prior to the test, the cats were allowed to acclimatise themselves in the examination room and the force plate for at least one hour. Then the cats were encouraged to jump onto the force plate by food, toys and by encouragement of the owner(s). The trial was performed by placing the cat on a table (1.0 m high) and gently moving it to the edge, from where it was encouraged to jump onto the force plate with its forelimbs landing first (Figure 1). Five valid trials were obtained from each cat for further analysis. The trial was considered to be valid if the cat landed correctly on the plate and continued to walk forward (Stadig and Bergh 2015).

Data analysis. The PVF (N), defined as the greatest vertical force measured during the landing phase, and the VI (N × s), defined as the sum of the vertical force during the landing phase, were calculated for each limb as the kinetic parameters used for the future analysis. In addition, for purposes of comparison, the PVF and VI were also normalised against each cat's BW and then expressed as a percentage of the BW, which was %BW and %BW/t, respectively. Therefore, the non-normalised and normalised kinetic parameters mean before and after those parameters being normalised against each cat's BW.

The symmetry index (SI) between the left and right limbs, defined as a percentage of the difference between the two limbs relative to the mean of the two limbs for the same kinetic variable, was calculated using the following equation (Voss et al. 2007):

$$\text{SI (\%)} = \frac{|X_R - X_L|}{0.5\ |X_R + X_L|} \times 100 \qquad (1)$$

where:

X_R – mean value of the PVF or VI of the right limb;

X_L – mean value of the PVF or VI of the left limb.

Additionally, an SI of 0% would represent the ideal symmetry between the right and left limbs.

Statistical analysis. SPSS 17.0 (SPSS Inc., Chicago, IL, USA) was used for all the statistical analyses. An independent sample *t*-test was used to identify the statistically significant differences between the thin and heavy group regarding the kinetic parameters, and a paired *t*-test was used to detect the statistically significant differences between the left and right forelimbs or hind limbs, or between the forelimbs and hind limbs within each group. All the data are presented as means ± SD (standard deviation) and the significance level was set at $P < 0.05$. In addition, Spearman's rank correlation coefficients were used to assess the associations between the BW and the kinetic parameters.

RESULTS

Kinetics

As shown in Table 1 and 2, the mean values of the non-normalised PVF and VI of the left and right forelimbs or hindlimbs were found to be significantly smaller in the thin cats than the heavy cats. The mean values of the non-normalized PVF and VI of the forelimbs and hindlimbs were also significantly smaller in the thin cats than the heavy cats. However, following the BW normalisation of these parameters, the mean PVF and VI of the left and

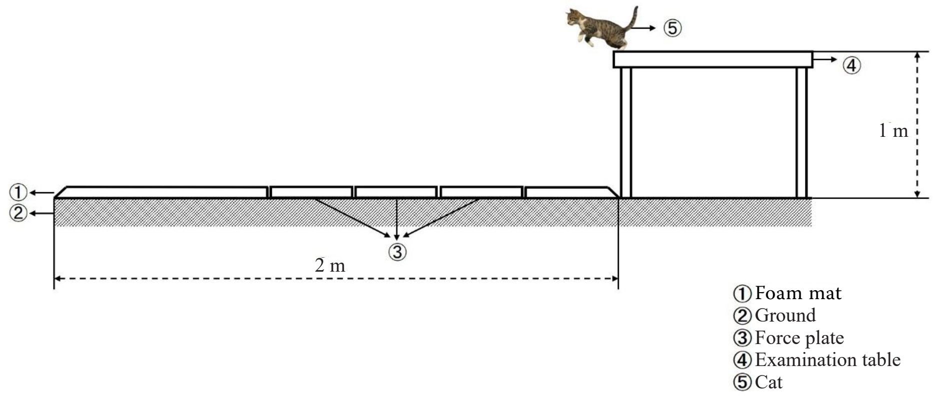

Figure 1. The adaptation of the force plate for the kinetic analysis during the cats' jumping

The length between the force plate and the examination table changes according to the distance that the cats' jumped

Table 1. The comparison of the kinetic parameters between the left and right sides of the forelimbs and hindlimbs for the thin and heavy groups

Forelimb					Hindlimb				
Variable	thin group	heavy group	*P*-value	Power	Variable	thin group	heavy group	*P*-value	Power
	mean ± SD	mean ± SD				mean ± SD	mean ± SD		
Left forelimb PVF (N)	66.02 ± 3.04	112.67 ± 4.51	0.000	1	Left hindlimb PVF (N)	23.89 ± 4.16	74.48 ± 3.61	0.000	1
Right forelimb PVF (N)	66.89 ± 2.54	113.83 ± 5.61	0.000	1	Right hindlimb PVF (N)	23.66 ± 3.96	75.04 ± 4.02	0.000	1
***P*-value | Power**	0.168 | 0.82	0.251 | 0.68			***P*-value | Power**	0.415 | 0.43	0.540 | 0.31		
Left forelimb PVF (%BW)	252.27 ± 14.03	212.75 ± 8.65	0.000	1	Left hindlimb PVF (%BW)	91.24 ± 15.80	140.74 ± 6.75	0.000	1
Right forelimb PVF (%BW)	255.69 ± 13.71	214.93 ± 10.37	0.000	1	Right hindlimb PVF (%BW)	90.39 ± 15.28	141.66 ± 7.03	0.000	1
***P*-value | Power**	0.162 | 0.83	0.251 | 0.68			***P*-value | Power**	0.438 | 0.42	0.550 | 0.26		
Left forelimb VI (N × s)	7.95 ± 0.70	13.47 ± 0.75	0.000	1	Left hindlimb VI (N × s)	4.38 ± 0.39	9.56 ± 0.38	0.000	1
Right forelimb VI (N × s)	7.96 ± 0.59	13.41 ± 0.80	0.000	1	Right hindlimb VI (N × s)	4.30 ± 0.48	9.51 ± 0.49	0.000	1
***P*-value | Power**	0.945 | 0.07	0.641 | 0.25			***P*-value | Power**	0.107 | 0.92	0.647 | 0.21		
Left forelimb VI (%BW × s)	30.42 ± 3.19	25.43 ± 1.54	0.000	1	Left hindlimb VI (%BW × s)	16.73 ± 1.57	18.03 ± 0.75	0.000	0.99
Right forelimb VI (%BW × s)	30.46 ± 2.84	25.33 ± 1.55	0.000	1	Right hindlimb VI (%BW × s)	16.41 ± 1.84	17.96 ± 0.91	0.000	0.99
***P*-value | Power**	0.930 | 0.07	0.627 | 0.21			***P*-value | Power**	0.100 | 0.93	0.643 | 0.15		

BW = body weight; PVF = peak vertical force; SD = standard deviation; VI = vertical impulse

Table 2. The comparison of the kinetic parameters between the forelimbs and hindlimbs for the thin and heavy groups

Variable	Thin group	Heavy group	*P*-value	Power
	mean ± SD	mean ± SD		
Forelimb PVF (N)	66.46 ± 2.81	113.25 ± 5.08	0.000	1
Hindlimb PVF (N)	23.78 ± 4.03	74.76 ± 3.80	0.000	1
***P*-value** | **Power**	0.000 | 1	0.000 | 1		
Forelimb PVF (%BW)	253.98 ± 13.86	213.84 ± 9.53	0.000	1
Hindlimb PVF (%BW)	90.82 ± 15.42	141.15 ± 6.85	0.000	1
***P*-value** | **Power**	0.000 | 1	0.000 | 1		
Forelimb VI (N × s)	7.96 ± 0.64	13.44 ± 0.77	0.000	1
Hindlimb VI (N × s)	4.34 ± 0.44	9.54 ± 0.43	0.000	1
***P*-value** | **Power**	0.000 | 1	0.000 | 1		
Forelimb VI (%BW × s)	30.44 ± 2.99	25.38 ± 1.53	0.000	1
Hindlimb VI (%BW × s)	16.57 ± 1.70	18.01 ± 0.83	0.000	0.99
***P*-value** | **Power**	0.000 | 1	0.000 | 1		

BW = body weight; PVF = peak vertical force; SD = standard deviation; VI = vertical impulse

Table 3. The comparison of the SI between the left and right sides of the kinetic parameters for the thin and heavy groups

Variable	Thin group	Heavy group	*P*-value	Power
	mean ± SD	mean ± SD		
SI of PVF for forelimb	4.04 ± 3.46	3.10 ± 3.63	0.309	0.26
SI of PVF for hindlimb	6.21 ± 2.44	5.46 ± 3.44	0.339	0.25
***P*-value | Power**	0.011 | 0.98	0.023 | 0.96		
SI of VI for forelimb	4.71 ± 4.12	3.52 ± 2.93	0.204	0.36
SI of VI for hindlimb	5.82 ± 2.92	5.19 ± 3.21	0.427	0.20
***P*-value | Power**	0.254 | 0.49	0.050 | 0.89		

PVF = peak vertical force; SD = standard deviation; SI = symmetry index; VI = vertical impulse

right forelimbs, or the forelimbs overall, were found significantly smaller in the heavy cats than the thin cats while the mean PVF and VI of the left and right hindlimbs, or the hindlimbs overall, remained significantly smaller in the thin cats when compared with the heavy cats.

No significant differences occurred in the non-normalised or normalised PVF and VI between the left and right forelimbs or hindlimbs in either group. However, in both groups, the non-normalised or normalised PVF and VI were all larger at the forelimbs.

Symmetry

The SI of kinetic parameters between the left and right limbs of the thin and heavy cats are described in Table 3. No significant differences were found in the SI of the PVF or the VI between the thin and heavy cats. However, the SI of the PVF was significantly smaller at the forelimbs than the hindlimbs in both groups.

Correlations

There were significantly high positive correlations between the BW and the non-normalised kinetic parameters. However, after the BW normalisation of these parameters, the PVF and VI of the forelimbs were significant and negatively correlated with the BW. The PVF and VI of the hindlimbs remained positively correlated with the BW although the correlation between the BW and VI of the hindlimbs was much weaker (Table 4).

Table 4. Spearman's rank correlation coefficient between the BW and the kinetic parameters of the forelimbs and hindlimbs of the thin and heavy groups

Variable	Forelimb	Hindlimb
PVF (N)	0.77	0.82
PVF (%BW)	−0.86	0.75
VI (N × s)	0.70	0.77
VI (%BW × s)	−0.82	0.29

BW = body weight; PVF = peak vertical force; VI = vertical impulse

DISCUSSION AND CONCLUSIONS

This study aimed at comparing the kinetic parameters of the landing following the jumping performance in the cats with the different BWs using a force plate. A further aim was to determine the associations between the BW and the kinetic parameters. The results of this study demonstrate that most of the kinetic parameters of the thin cats were significantly smaller than the heavy cats during the landing and these values increased as the BW increased, except for the normalised PVF and VI of the forelimbs. These results supported our hypotheses that the thin cats would have different kinetic gait patterns during the landing than the heavy cats and that the BW would be associated with the magnitude of the kinetic variables produced. These results are important in establishing reference values for the kinetic parameters of the landing after the jumping in clinically intact cats for further investigation in the future.

In our study, the mean values and the proportion of the PVF and VI obtained seem to be larger than the values recorded in a previous study (Lascelles et al. 2007). This may be associated with the differences in the technical equipment and the measurement techniques used to quantify the parameters of interest. Previous studies (Lascelles et al. 2007; Stadig and Bergh 2015) used a pressure-sensitive walkway for the kinetic analysis of the walking and jumping in cats, while this study utilised a force plate. Moreover, the studies (Besancon et al. 2003; Lascelles et al. 2006) compared the differences between the pressure-sensitive walkways and the force plates in the biomechanical motion analysis of small animals, and have reached a consensus that the ground reaction force data from the pressure-sensitive walkway and force plate differs, as the values derived from the pressure-sensitive walkway are slightly lower than those derived from the force plates. This could partly explain the value differences observed between this study and the others.

All the non-normalised kinetic parameters of the landing were significantly smaller in the thin cats than the heavy cats and increased as the BW increased. These results are consistent with Newton's second law that force is a function of mass (Kim et al. 2011). However, after these parameters were normalised against the BW, significant negative correlations between the normalised PVF, VI and BW of the forelimbs were observed. The correlation differences between these parameters before and after the normalisation have also been previously reported (Budsberg et al. 1987; Kim et al. 2011). For example, Kim et al. (2011) compared the temporo-spatial and kinetic parameters for the forelimbs and hindlimbs of small and large dogs during walking and further determined the associations between the temporo-spatial variables, kinetic variables, and BW within and between the two groups. They found a negative correlation between the normalised PVF and BW in large dogs. In addition, in a study by Schnabl-Feichter and others (Schnabl-Feichter et al. 2017), there were no correlations between the body weight (BW) and the PVF after the normalisation to the %BW while a correlation between the BW and the VI was still detected. However, the animal species and the motion involved in the above studies were different from this study, which would make this kind of analogy lack validity and generalisability. Therefore, more research focused on the biomechanical analysis of the landing in cats is needed in order to generalise the results obtained here.

A previous study (Stadig and Bergh 2015) has demonstrated that cats landed with both forelimbs and then the hind limbs symmetrically in relation to the forelimbs during the jumping, which mean that the forelimbs would dominate during the landing phase. The results of this study that the non-normalised and normalised PVF and VI of the forelimbs were significantly larger than those of the hindlimbs in both groups would also support this statement. However, our results showed that the normalised PVF and VI of the forelimbs were significantly smaller in the heavy cats while these parameters in the hindlimbs were significantly larger in the heavy cats when compared with the thin cats. In combination with Figure 2 below, it is possible, that the pattern of landing may be different between the thin and heavy cats with the hindlimbs of the heavy cats becoming more involved during the landing, which may explain the smaller normalised PVF and VI values of the forelimbs in the heavy cats.

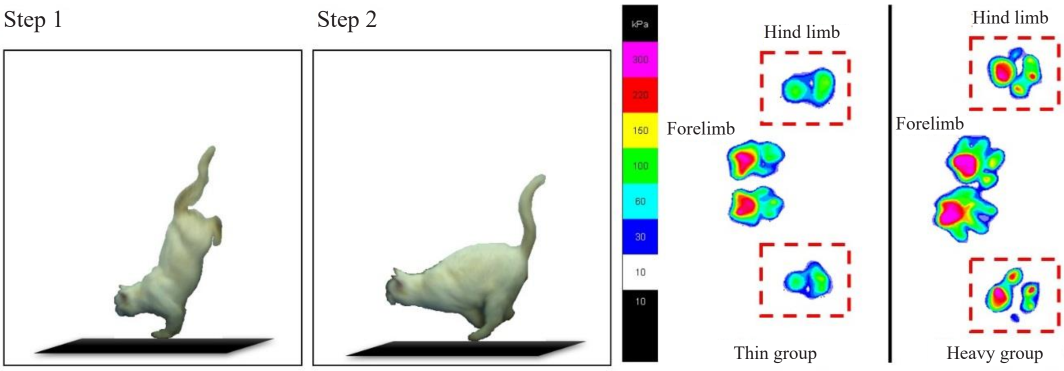

Figure 2. The comparison of the landing patterns of the thin and heavy cats

The "red square" indicated a difference in the landing pattern between the thin and heavy cats

Symmetry is often assumed to be a characteristic of a normal gait and changes in the symmetry have been associated with lameness (Voss et al. 2007; Lequang et al. 2010; Kim et al. 2011). No studies have focused on the SI of cats during the jumping n spite of them exhibiting an excellent jumping ability. Lascelles et al. (2007) evaluated the kinetic parameters during the cats' jumping and found no significant differences between the left and right forelimbs. However, they did not calculate the SI of the limbs during the landing. The determination of the SI is important as it could be fundamental in the future diagnostics of cats' diseases that may affect the musculoskeletal system. In the present study, the SI of the PVF was significantly smaller in the forelimbs than the hindlimbs in both groups, suggesting that the forelimbs, as the dominant legs during the landing, landed more symmetrically than the hindlimbs. Furthermore, the SI of the PVF and VI for the hind limbs are smaller in the heavy cats although they failed to reach any significance, which may also indicate that the hindlimbs of the heavy cats become more involved during the landing.

Several limitations existed in this study. Firstly, the cats recruited for this experiment were divided into two groups according to the BW as a thin or heavy group. In a previous study (Kim et al. 2011), the authors demonstrated that any linear correlation is sensitive to outliers in the data and that the overall correlation for two distinct groups would be misleading if the results were simply pooled for each group. This may explain the high values recorded for the correlations between the BW and the kinetic parameters measured in this study. Therefore, future studies should include medium-sized cats which will help reach more precise correlations between the BW and the kinetic parameters measured. In addition, some of the comparisons made, in this study, had statistical power levels lower than 0.8 owing to the small number of cats in each group. While a power level of 0.8 is generally required to minimise a type two error or false negative, the analysis and results in this study did provide interesting statistical trends (Verdugo et al. 2013). However, further research should consider increasing the numbers of cats used, thus, reducing the chance of any type two errors.

The study compared the kinetic parameters of the landing in cats with different BWs and determined the associations between the BW and the kinetic parameters. Through the study, we can provide more reference data for the biomechanical motion analysis related to jumping in clinically intact cats. The results showed significant similarities and differences during the landing between the thin and heavy cats. Most of the kinetic parameters of the thin cats were significantly smaller than the heavy cats during the landing and these values increased as the BW increased, except for the normalised PVF and VI of the forelimbs. The SI of the PVF was significantly smaller in the forelimbs than the hindlimbs in both groups, which suggested that the forelimbs landed more symmetrically than the hindlimbs. In addition, the SI of the PVF and the VI for the hindlimbs are slightly smaller in the heavy cats than the thin cats. Combining these results, we demonstrated that there may be a difference in the landing pattern during the jumping between the thin and heavy cats. However, further investigations regarding the loading characteristics of the landing in cats are needed before this speculation can be further verified.

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Received: January 29, 2019
Accepted after corrections: October 14, 2019