Original Article

Investigation of the mechanical and grounding characteristics of the domestic cat's paw pads based on gait analysis

Ye Mei[1] Guolin Wang[1*] Haichao Zhou[1] Congzhen Liu[1*]

Abstract

The paw pads, which can produce moderate changes that are reflected in mechanical and grounding characteristics, play an important role for domestic cats in realizing their biological characteristics. The purpose of this study was to investigate these moderate changes of paw pads in various gaits i.e. walking, trotting and emergency stop gaits based on the ground reaction forces and contact strain experiments to obtain the mechanical and grounding shape representations. The results proved that with the change of gait, the representations changed obviously. For the ground reaction forces, the response of the fore paw pads was more sensitive than that of hind and the point of force also changed from the outside to the middle of the pads with the gait from walking to trotting. In addition, in the walking gait, the contact shape was in the natural state but the contact shape pointed to the inside deflection and appeared discrete in the trotting and emergency stop gait respectively. The peak value of contact principal strain was little different between the three gaits but there were obvious differences in distribution characteristics and strain direction. These findings could help to understand the relationship between paw pads and cat biological characteristics.

Keywords: biomechanics, biological characteristics, cats, gait analysis, grounding characteristics, paw pads
[1]*School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang, China*
***Correspondence**: glwang@ujs.edu.cn* (G. Wang)
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Introduction

Animals of the feline family, a kind of the digitigrade, are good at running and jumping and exhibit biological characteristics such as attenuating ground impact strongly and grasping the ground firmly owing to their unique long carpal, tarsal and large paw pads (Brad *et al*., 2015). Among them, the paw pads, as the only body part in contact with the ground, play a decisive role in the realization of the biological characteristics (Whittle, 1999). Consequently, the mechanical characteristics of paw pads based on the various motion gaits has been investigated for many years, especially in domestic cats (Clayton *et al*., 2001; McLaughlin, 2001; Nunamaker *et al*., 1985; Pantall *et al*., 2012). Especially, the use of pressure sensing walkways to kinetic analysis has been reported more frequently (Kim *et al*., 2011). For example, Motoshi (Motoshi *et al*., 2006) studied the mechanical characteristics of the fore and hind paw pads of domestic cats in motion and Matijevich (Matijevich *et al*., 2019) found the difference in GRFs (ground reaction forces) of male and female cats in the walking gait. Also, related researches have concluded that the paw pads have the following different mechanical characteristics in different motion processes: in order to reduce the impact force, the paw pads should have a certain flexibility; in order to transfer the ground support force, they should have a certain stiffness; and in order to contact the ground stably, they should have a certain damping quality. Meanwhile it has also been verified that the paw pads can produce adaptive changes in different gaits to facilitate the effective play of biological characteristics (Chi, 2005; Huaibin *et al*., 2017; Qian *et al*., 2014). These adaptive changes in various gaits in the contact process between the paw pads and ground are specially evolved biological characteristics because of the long-term survival of domestic cats. Knowledge of these changes which are reflected in mechanical and grounding characteristics will provide a better understanding of the mechanism of realizing biological characteristics and could allow for better bionic application. However, most researches in the past that paid more attention to the GRFs of paw pads just at velocities simply from 0.37 to 0.85m/s were only in the single gait (Lascelles *et al*., 2007) and there have been few studies paying attention to the grounding characteristics analysis of paw pads which could be closely related to the mechanism of realizing biological characteristics.

The purpose of this study was to investigate paw pads' mechanical and grounding characteristics in domestic cats exercising in various gaits. The intent was to find the adaptive changes in GRFs of paw pads in gaits such as walking and trotting. Secondly, the changes of contact shape and contact principal strain of the paw pads on the contact surface were studied to characterize the domestic cat's active adjustment in the gaits of walking, trotting and emergency stopping.

Materials and Methods

Ethical statement: All procedures used in the animal experiments were approved by the Faculty of Veterinary Science Animal Ethics Committee of Jiangsu University (No.2019-0016).

Domestic cats included for the experiments: Eight different kinds of domestic cats (4 males and 4 females) of different body types were used in this study and permission to use the cats in the study was obtained from their owners. The domestic cats were adult cats whose ages were between 4 and 7 years; their weights ranged from 3.8 to 5.6 kg; and their height measured, at the highest point of the shoulders, 20 to 28 cm. The variation in body type, size and age was a deliberate measure to improve reproducibility and hence, reliability, of any outcome (Gustas *et al*., 2004). Also, they all had no recorded histories of musculoskeletal disorders and their feet were intact and healthy.

Experimental contents and procedures: This study included two experiments. One was GRFs experiment; the other was the contact strain experiment and the two experiments were carried out after the domestic cat's full adaptation to the experiment and environment through at least a week of training.

The kinetic parameters in GRFs experiment were measured with a pressure-sensitive walkway (Walkway A101; Tekscan, the USA) and analyzed using designated software (Walkway7.70; Tekscan, the USA). After having equilibrated and calibrated the sensors of the pressure-sensing walkway using a phantom as reported previously (Agostinho *et al*., 2012), each domestic cat was stimulated to walk across the pressure blanket at different velocities and gaits in a straight line with the help of toys and food. During the motion, a high-speed camera (Olympus i-SPEED 3, Japan）with a sampling frequency set to 200Hz was used to record the gaits and speed of domestic cats. The velocity range of walking gait was from 0.40 to 1.00 m/s, and that in trotting gait was between 1.2 and 2.0 m/s (Liu *et al*., 2020; Qian *et al*., 2014).

The contact strain experiment was measured using the Vic-2D（CSI VIC-2D, the USA）, which is an innovative system that uses a non-invasive method called the Digital Image Correlation (DIC) technique. It uses only one high-resolution couple charged device camera to capture the moving images of the subjects and DIC tracks the gray distribution level in subsets of images of the specimen's surface covered with natural contrast or painted with a random black-white speckle pattern to determine displacement and strain fields of the material under any type of loading. In this experiment, a glass plate was used as the substrate. After spraying speckle on the paw pads, they were allowed to move straight ahead on the substrate in walking, trotting and emergency stopping gaits; a high-speed camera installed under the substrate captured the moving images which were captured at 200 frames per second.

Statistical method: For the data in the experiments, the values were expressed as the means ± standard deviation at a percent of the body weight (%BW) after statistical analysis of all the data. The statistical analysis method that was used was ANOVA and a student's *t*-test was performed to determine the statistical significance of the data at *P* of 0.05.

Results

Comparison of the mechanical characteristics in walking and trotting gaits: For domestic cats, there were no significant differences in the kinetic parameters between the male and female cats and between the left and right fore paw pads or the left and right hind paw pads (Mirela *et al*., 2013).Therefore, the data on paw pads was divided into two groups which were fore paw pads and hind paw pads in the walking or trotting gait, as listed in Table.1. Significant differences were found between the fore and hind paw pads in peak GRFs and the percentage of body distribution by comparison. It showed that the peak GRFs of the fore paw pads was much larger than that of the hind paw pads whether it was in the walking or trotting gait. When the gait changed from walking to trotting, the peak GRFs also increased significantly; especially in the fore paw pads. In addition, the percentage of body distribution indicated that the fore paw pads bore more force than the hind paw pads in the process of movement. The obvious gap was in the trotting gait which was (57.9±2.3) percentage of body in the fore paw pads and (42.8±1.8) percentage of body in the hind paw pads. In order to further understand the kinetic parameters of each toe pad, Table.2 shows the comparison of the data between the fore and hind toe pads in different gaits. The domestic cat's toe pads can be divided into five areas: second pad (2nd), third pad (3rd), fourth pad (4th), fifth pad (5th) from the inside to the outside of the paw pads and metacarpal pad (M-pad). The data in Table 2 shows that the 3rd, 4th and M-pad of the paw pads were the main parts of bearing the GRFs and the M-pads in fore or hind paw pads were the largest. In addition, the peak GRFs of M-pad of the fore paw pad in the trotting gait was obviously bigger than that of the walking gait, while that of the hind paw pads basically did not show much difference when the gaits changed.

Table 1 Comparison of the data between fore and hind paw pads in gaits of domestic cats (The percentage of body distribution among the fore or hind paw pads was calculated as follows: (total peak GRFs of the fore or hind pads / total peak GRFs of the fore and hind pads) × 100.)

Gaits	Walking		Trotting	
Site	Fore paw pads	Hind paw pads	Fore paw pads	Hind paw pads
Peak GRFs in paw pad /(%BW)	64.4±8.7	46.6±6.1	85.4±9.6	59.6±8.2
Percent of body distribution	52.2±1.8	47.4±1.6	57.9±2.3	42.8±1.8

Table 2 Comparison of the data between fore and hind meat pads in gaits of domestic cats

Gaits	Peak GRFs in fore meat pads /(%BW)					Peak GRFs in hind meat pads /(%BW)				
	2nd	3rd	4th	5th	M-pad	2nd	3rd	4th	5th	M-pad
Walking	10.9±1.3	14.6±2.3	10.6±1.8	8.7±1.1	37.2±4.4	9.3±0.9	12.1±1.5	10.2±1.7	3.9±0.6	25.1±3.2
Trotting	8.9±1.0	12.6±1.6	13.4±1.6	8.6±0.9	50.2±6.3	8.4±1.1	14.2±1.8	12.1±1.6	4.3±0.8	24.2±3.8

Also, as shown in Fig.1, the contact time of the hind paw pad was a little longer than that of the fore paw pads during motion than that in walking gait, the contact time of fore and hind paw pads was 0.37s and 0.43s respectively, and that in the trotting gait was 0.15s and 0.19s respectively in the sample. In addition, as shown in Fig.2, with the increase of impact because of the gait change from walking to trotting, the force points of peak GRFs of the digital pads also changed from the outside of the pads (2nd and 3rd pads) to the middle of the pads (3rd and 4th pads), especially in the hind paw pads. The effect of metacarpal pad bearing the GRFs was further expanded, especially in the fore paw pads.

Comparison of grounding characteristics in the three gaits: As mentioned above, the peak GRFs and percentage of body distribution of the fore paw pads were more prominent compared with the hind paw pads, hence, the fore paw pads were chosen as the main object to analyze the differential characteristics of paw pad in contact shape and contact strain among the walking, trotting and emergency stop gaits.

With the help of DIC technique, the reconstruction of the contact shape of the paw pads at three different gaits was completed in the coordinate system, as shown in Fig.3. As we can see, the contact shape of the paw pads changed obviously when it was completely attached to the ground under the different gaits. In the walking gait, the contact shape was the same as that of the cat's paw pad in the natural state and the toe pads were a natural extension. In the trotting gait, the contact shape showed an inclination towards the inner side of the body and while in the emergency stop gait, the contact shape appeared discrete and the distance between the toe pads was significantly larger than that in the walking gait. The max stable contact area of fore left paw pads in the three gaits is shown in Table.3 which indicates that the contact area of trotting and emergency stop gaits was much bigger than that of walking gait.

Based on designated software in VIC-2D system, the contact principal strain and direction information in the whole contact process for the three gaits was acquired. From Fig.4, it is found that the strain on paw pads is mainly tensile strain and the compression strain appears locally for the walking gait and trotting gait but for the emergency stop gait, the strain of digital pads is mainly compression strain and that of the metacarpal pad is mainly tensile strain. Also, the peak principal strain values of the pads for the three gaits were almost the same, most of them appeared at the edge of the toe pads and ranged from 13% to 16%. The difference was that with the change of gaits from walking to trotting to emergency stop, the area of peak principal strain increasing gradually. By comparing the contact principal strain direction of the paw pads, a completely different trend was found for the three gaits. Comparing the contact principal strain direction it showed disordered back and forth changes for the walking gait but that in trotting gait and emergency stop gaits showed regular and fixed feature in the whole contact process. For the walking gait, the contact principal strain direction distribution of the pad was firstly directed to the inside and then that of the digital pads gradually changed and pointed to the outside, while that of the metacarpal pad mainly pointed to the back of the movement direction. For the trotting gait, the contact principal direction distribution of the four digital pads were separately the same as that of the hind metacarpal pad, which could be considered as a continuous flow field and gradually formed the direction from two sides to the middle. For the emergency stop gait, the contact principal direction distribution showed a similar trend with the trotting gait but in the opposite direction which gradually formed the direction from the middle part to the two sides. In addition, in these two gaits, the areas with the largest value of contact principal strain appeared in the inner side of the paw pads.

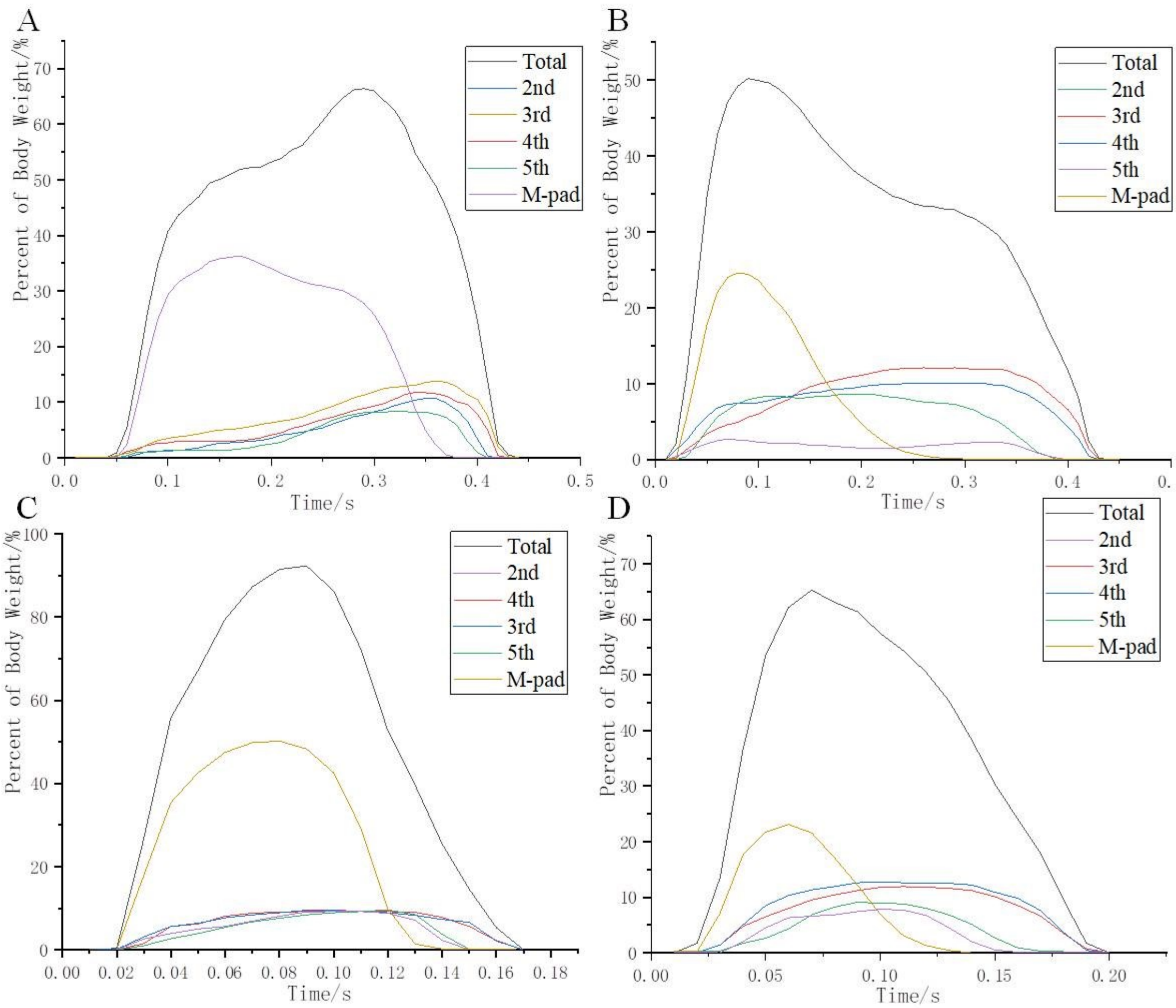

Figure 1

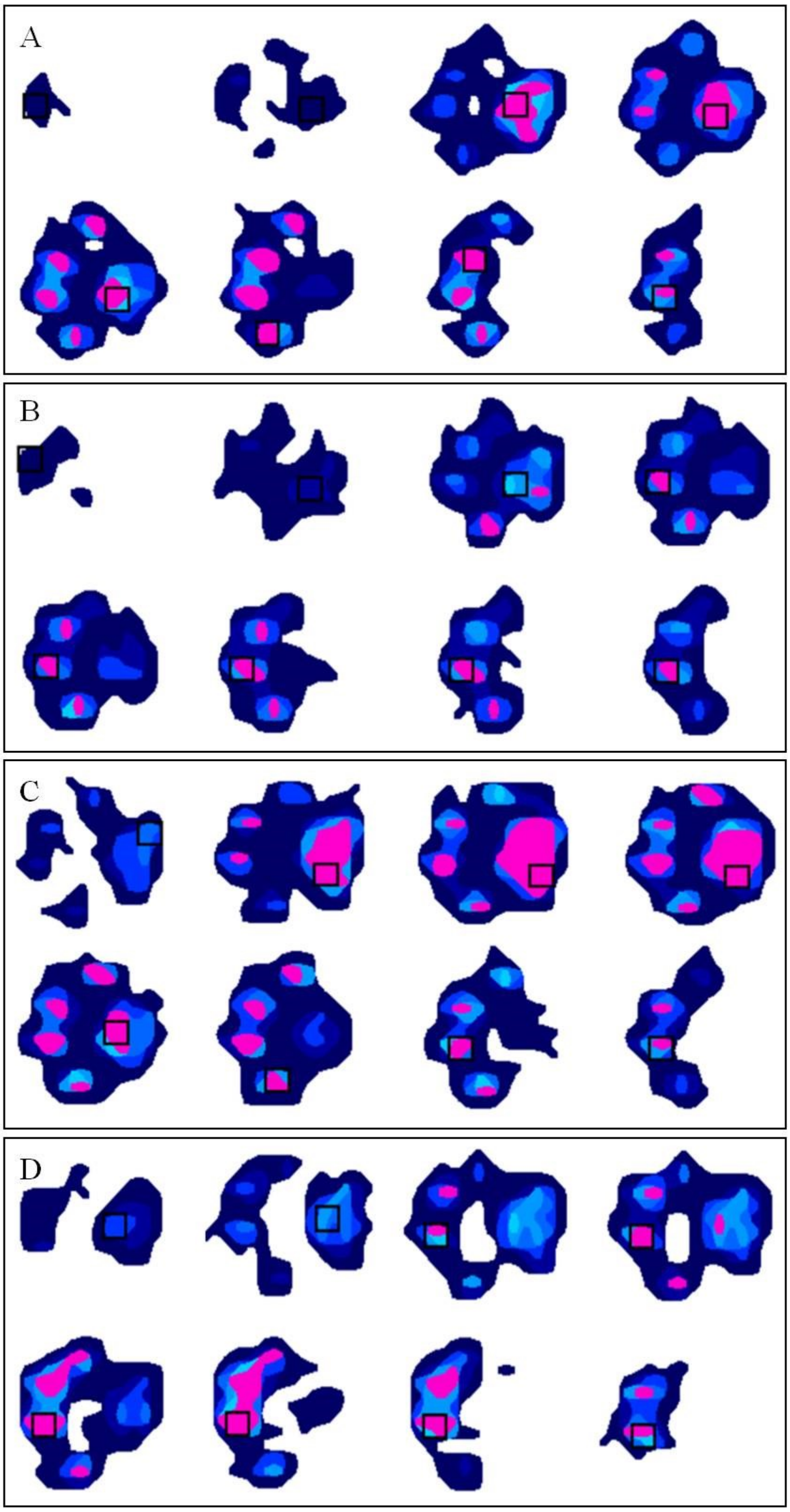

Figure 2

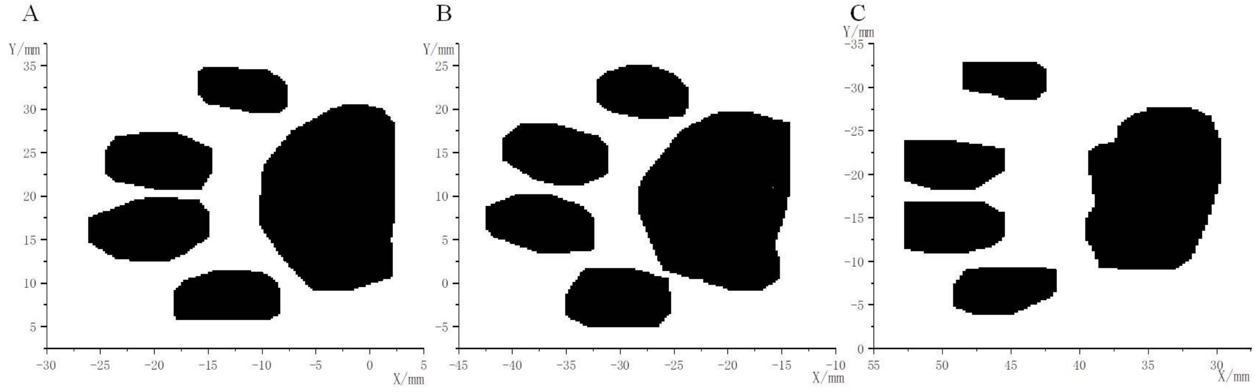

Figure 3

Table 3 The max contact area of fore paw pads in three gaits

Gaits	Max area /*mm*^{2}
Walking	662±11.74
Trotting	778±16.99
Emergency stop	752±12.28

Discussion

In the feline family, the moderate changes in paw pads during the different gaits is also a powerful variable in predicting many characteristics which are similar to their body size partly describing variations in relevant features (Huang *et al*., 2000).

By comparing the GRFs characteristics of fore and hind paw pads in one same gait, the GRFs response of the fore paw pads is more sensitive than that of hind, which also shows that the fore paw pads play a more critical role in the realization of biological characteristics. These characteristics can be explained by the functional difference for forelimb-dominant and hindlimb-driven (Liu *et al*., 2020). Hence, the fore paw pads ensure the safety of the body by bearing more impact which may be two to three times the size of their body weight per limb during motion (Biewener, 1990) and at the same time controls the forward direction. Also, with the gait changed from walking to trotting, the impact between the paw pads and the ground increases, the peak GRFs of fore paw pads, especially the metacarpal pad in the fore paw pads, have a significant response change, i.e their peak GRFs are significantly increased from 37.2±4.4 %BW to 50.2±6.3 %BW. This is mainly because, compared with the digital pads, the metacarpal pad which has viscoelastic mechanical properties, has a larger volume and contact area and hence more impact energy can be absorbed through the change response at the metacarpal pad. In addition, the force points of peak GRFs of the digital pads change and are from the outside pads (2nd and 3rd pads) to the middle pads (3rd and 4th pads), especially in the hind paw pads with the gaits from walking to trotting. This is mainly because the bone structure of the middle digital pads is more obvious in bow features than that of other digital pads, which can be more conducive to energy storage and shock absorption which are caused by an increase in the speed of motion.

The contact shape for the walking, trotting and emergency stop gait also has understandable changes. In the walking gait, the contact time is the longest and this makes the paw pads have enough time to adapt and adjust in the whole contact process. But in the trotting and emergency stop gaits, because of the shorter contact time, the best posture of the paw pads must be ready in order to meet the motion mechanics. The change of the paw pad inclines to the outside of the paw in the trotting gait of the domestic cats. Through the coupling of the two paw pads at the front and back, the interlocking mechanism of the ground is realized and this is conducive to the improvement of the grip ability in the process of fast running. The more scattered changes of the paw pad in the emergency stop gait of the domestic cat can be regarded as the self-locking mechanism of the paw pads, which is more conducive to the connection between each meat pad and the ground. The contact force can increase the resistance and adsorption on the ground in the process of movement, so as to obtain the required grip during the emergency stop process.

According to the difference in contact principal strain in the three gaits, the change in the contact process of paw pads is also conducive to the realization of biological characteristics. Honert unravels the specific tissues in the human body that are responsible for the majority of the soft tissue work; inherent body soft tissues execute mechanical work by wobbling and deforming (damping spring effect). They report that, the foot contributes approximately 60–70% and 80–90% of the soft tissue work during level and uphill walking and during downhill walking respectively (back sole contact to the front sole contact landing process) (Honert *et al*., 2019). Our experiment results confirm the contact process of paw pads to be in the sequence of digital pads to metacarpal pad then digital pads and this process has more cushioning advantage than the process of only from back sole contact to the front sole in human or other plantigrades. Besides, in the walking gait, the disordered back and forth changes of contact principal strain direction can be considered as a damping spring in which the whole digital pad may be regarded as the spring part and the metacarpal pad as the damping part. The jointed work of them makes for the better cushioning performance of the paw. In the trotting gait, the outside to inside direction of contact principal strain is beneficial to reduce the contact area and the resistance in running. However in the emergency stop gait, the inside to outside direction of contact principal strain can enlarge the contact area and increase the resistance of movement to provide the grip needed in the emergency stop process and convert the energy into friction energy and internal energy to achieve the emergency stop.

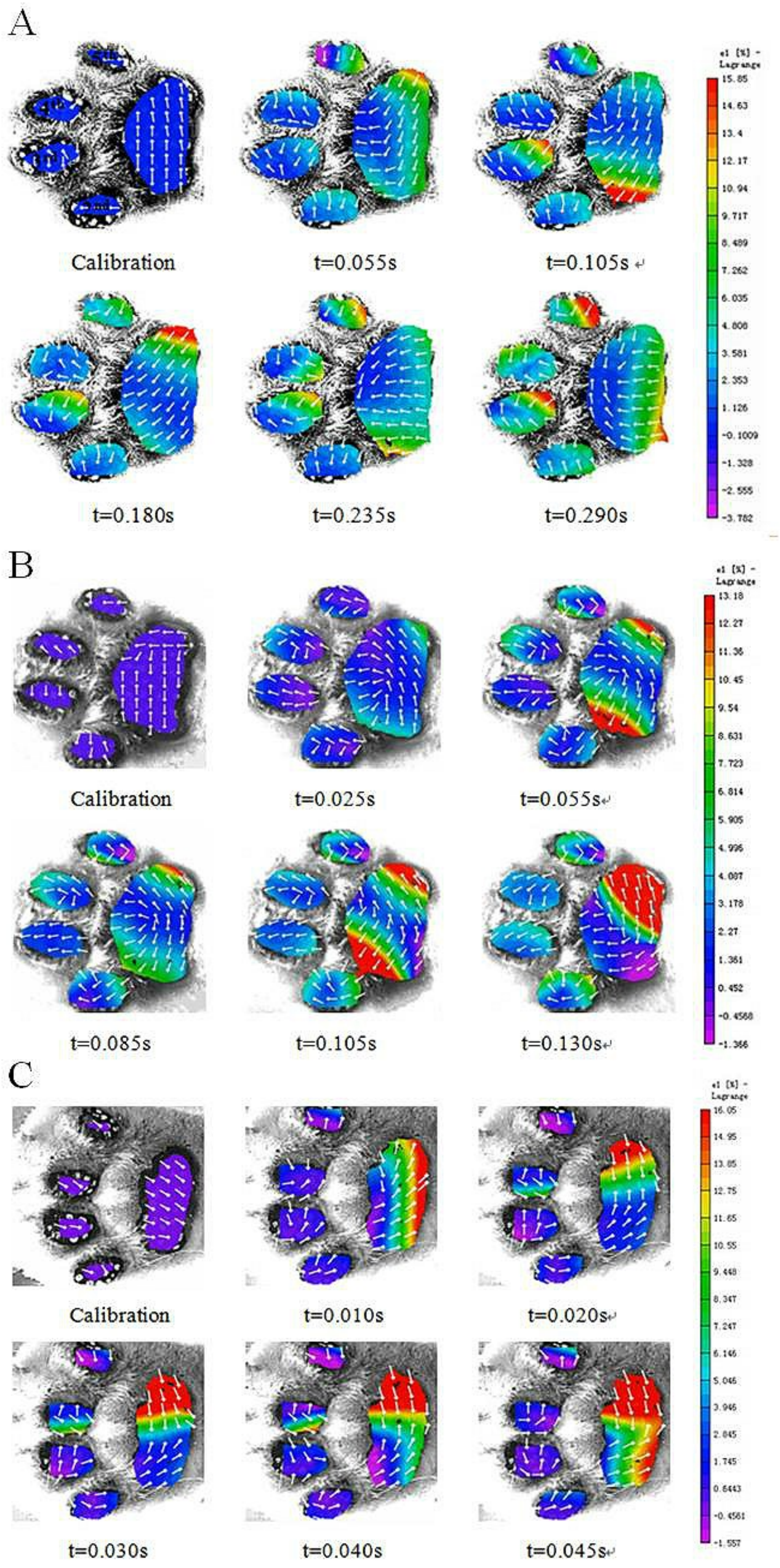

Figure 4

In conclusions, based on the GRFs experiment and the contact strain experiment, an exploratory study was conducted on the change responsible for the paw pad of domestic cats at various gaits. The adaptive adjustment of the paw pads in mechanical characteristics and shape during the location at various gaits was found and these changes were in order to better meet the needs of biological characteristics during the motion.

***Conflict of Interest*:** No author declares a competing interest.

***Authors contribution*:** Conceptualization and data curation: Ye Mei and Congzhen Liu; Investigation, methodology and writing-original draft: Ye Mei; Supervision and writing-review & editing: Guolin Wang and Haichao Zhou. All authors have read and approved the final manuscript.

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