Title	Investigation on the cushioning characteristic of cat paw pad in motion: A synergy of its histological structure and kinematic mechanical characteristics
Author(s)	Mei, Ye; Wang, Guolin; Zhou, Haichao; Li, Jingsong; Liu, Congzhen; Yu, Kangying
Citation	Japanese Journal of Veterinary Research, 69(1), 19-30
Issue Date	2021-02
DOI	10.14943/jjvr.69.1.19
Doc URL	http://hdl.handle.net/2115/80617
Type	bulletin (article)
Additional Information	There are other files related to this item in HUSCAP. Check the above URL.
File Information	JJVR69-1_19-30_YeMei.pdf (本文)

Japanese Journal of Veterinary Research 69(1): 19-30, 2021

JJVR

REGULAR PAPER Experimental Research

Investigation on the cushioning characteristic of cat paw pad in motion: A synergy of its histological structure and kinematic mechanical characteristics

Ye Mei[1)], Guolin Wang[1,*)], Haichao Zhou[1)], Jingsong Li[2)], Congzhen Liu[1)] and Kangying Yu[1)]

[1)] School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang, China
[2)] College of Mechanical Engineering, Hainan University, Haikou, China

Received for publication, July 2, 2020; accepted, October 5, 2020

Abstract

The paw pads of cats had evolved to exhibit strong cushioning characteristic that could attenuate ground impacts effectively in motion. The purpose of this study was to explore the realization mechanism of the cushioning characteristic of paw pads. Ten adult domestic cats were included for this study and three experimental investigations, i.e histological experiment of tissues, ground reaction forces experiment and contact strain experiment of the paw pads in motion, were undertaken. The results of the study proved that the realization mechanism of the cushioning characteristic of the paw pads was a result of synergy of multiple factors. First, on the histological level, a multi-layer structure of the paw pads, which were made of the stratified epithelium layer, dermis layer and subcutaneous tissue layer, helped to achieve outward and inward contact stress and strain decaying. Next, the results from the ground reaction forces experiment showed that the fore-pads played a more important role than that of the hind in achieving cushioning characteristic. And the contact strain experiment revealed that, the movement characteristics of front-back and left-right swing deformation occurred in paw pads, especially in metacarpal pad, was beneficial to the exertion of the cushioning energy storage. The histological structure of paw pads revealed its natural advantage to realize the cushioning characteristic, but the mechanical characteristics were the acquired adaptive habits responsible for the realization of cushioning characteristic. These exploratory investigations gave the insights into the cushioning characteristic of the cat paw pad.

Key Words: Paw pads, Cats, Cushioning characteristic, Biomechanics, Microstructure

Introduction

The cats exhibit biological characteristics such as attenuating ground impacts strongly and griping with ground firmly in motion because of their unique carpals, tarsal and large paw pads[3)]. Among them, the paw pads, as the only part in contact with the ground, play a decisive role in the realization of the biological characteristics. Over the past decades, relevant mechanical characteristics of the cat paw pads, for example, nonlinear viscoelastic property and ground reaction forces (GRFs), had been investigated. Alexander[1)] examined the dynamic elastic properties of the paw pads of the domestic cats, and found it has non-linear elastic properties.

* Corresponding author: Guolin Wang, School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang 212013, China
Phone: +86-0511-88797620. Email: glwang@ujs.edu.cn
doi: 10.14943/jjvr.69.1.19

Biewener[2] found cats generally exert GRFs, which were two to three times the size of their body weight per limb. Chi[4] had done a lot of research on animal paw pads, and concluded that, in order to reduce the impact force, the paw pads should have certain flexibility; in order to transfer the ground support force, they should have certain stiffness; in order to contact the ground stably, and they should have a certain damping characteristics. Zhang[27] conducted a preliminary analysis of the cushioning mechanical properties of the paw pads based on the GRFs when the cats landed. Ker[13] analyzed the landing impulses based on the GRFs and found that, the hind limbs played a major role in dissipating energy. Motoshi[17] measured the GRFs during the cat locomotion and then developed a model that allowed for the calculation of the magnitude and direction of the GRFs. Besides, different forms of locomotion had been studied in the cats[22]. All these researchers show that the cat paw pads have impact resistance or cushioning characteristic but still cannot reveal the mechanism of cushioning realization. Biological adaptation to the living environment presents various functions, not only the result of a single factor, but also the result of multiple factors through appropriate mechanism to realize. Hence, it is necessary to have a deeper study in the cats, like the plantigrades[7,8,12,19,20], which have received extensive systematic study at the microscopic and macroscopic level, to reveal the mechanism for the realization of this cushioning characteristic of cats' paw pads.

The purpose of this study is to explore the biological mechanism responsible for the realization of the cushioning characteristic of domestic cats' paw pads. Thus, ten adult domestic cats are included for this study, and three experimental investigations, i.e histological experiment of pad tissues; GRFs experiment and contact strain experiment of the paw pads in motion, are undertaken.

Materials and Methods

Domestic cats included for the experiments

For the ten domestic cats in this study, two cats had died from the heart disease and came from the Jilin Animal Hospital that were used for histological experiment; the others clinically healthy cats recruited from client owned or shelter-owned were used in the kinematic experiment. The clinically healthy cats were adult cats whose age was (5.6±1.8) years old, their weights were (4.3±1.2) kg and their height measured at the highest point of the shoulders were (23±1.7) cm. The variation in body type, size, and age was a deliberate measure to improve reproducibility, and reliability, of any outcome. Besides, they all had no recorded histories of musculoskeletal disorders and their feet were intact and healthy.

The histological experiment

The purpose of the histological experiment was to observe the tissues section of cat paw pads by a biological microscope to obtain their microstructure. The histology procedures in the experiment mainly included the extraction of paw pad tissue, fixation of specimens, water washing and alcohol dehydration, wax soaking, embedding, deparaffinization and dyeing. In the light of it, the tissue samples were taken from the digital pads and metacarpal pad; Then the tissue samples were kept into a 4% parformaldehyde solution for up to 24 hours for fixation before water washing and alcohol dehydration; Next, 5-um-thick slices were extracted by cutting the tissue samples after wax soaking in warm box; Finally, the slices were stained with haematoxylin and eosin stained after deparaffinization and priored to the histological experiment with the medical biomicroscope (Olympus IXplore SpinSR, Japan).

The histological finite element model

Based on the histological structure of cat paw pads, a digital model of the paw pad and a contrast model were constructed by using

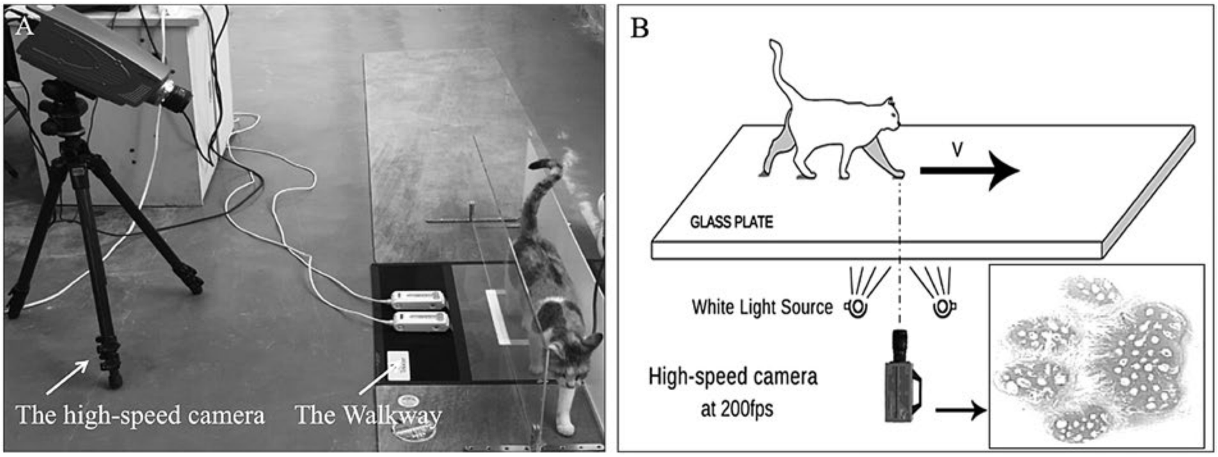

Fig. 1. The two experiments were included in kinematic experiments of paw pads. "A" was the GRFs experiment; "B" was the contact strain experiment.

the ABAQUS software in order to investigate the biomechanical function in cushioning characteristic. The FE simulations were conducted to analyse the biomechanical function of the models in contact with ground which was defined to contact the ground vertically with an initial velocity ranging from 0.2 m/s to 1.4 m/s.

The force-displacement experiment of paw pads

In order to understand the stiffness characteristics of the cats' paw pads, the stiffness of each pads were tested. In the process of the experiment, the flat head indenter was selected. A force of 20 N was applied to the metacarpal pad of the front and hind pads on the tension and compression testing machine, while the force of 10 N was applied to the digital pads of the front and hind pads. The loading speed was set at 5 mm/min. Besides, in order to ensure the validity of the data, two of the eight cats were selected for this experiment, and after the weight of the two cats were measured on the electronic scale, the appropriate amount of anesthetic was prepared in the pet hospital and the cat was anesthetized for about 15 minutes. After the end of the experiment, the cats did not have any adverse reactions, and can continue to participate in the kinematic experiments.

The kinematic experiments

The healthy domestic cats were used for the kinematic experiments at gait motion conducted in two parts: one was acquisition of paw pads' GRFs; the other was contact strain experiment between paw pads and ground. The experiments were carried out after the domestic cat fully adapted to the experiments and the study only extracted the data of cats at the speed between 0.4 m/s and 0.8 m/s which was the best gait to show the strongest cushioning characteristic to analyze the kinematic mechanical characteristics[18,23].

GRFs experiment

The Walkway (Walkway High Resolution HRV4, Tekscan, USA), a pressure distribution measurement system was used in the pads' GRFs experiment in order to get the GRFs data between pads and ground. As depicted in Fig.1 A, after completion of system calibration, the cats were allowed to walk on the pressure blanket with various speeds in straight line. During the experiment, the pressure distribution data of cats under the same motion mode was collected 6 times in order to ensure accuracy and reliability of the acquired experimental data. The purpose of the high-speed camera (Olympus i-SPEED 3, Japan) with a sampling frequency set to 200 Hz was to record the walking gaits and speeds of the

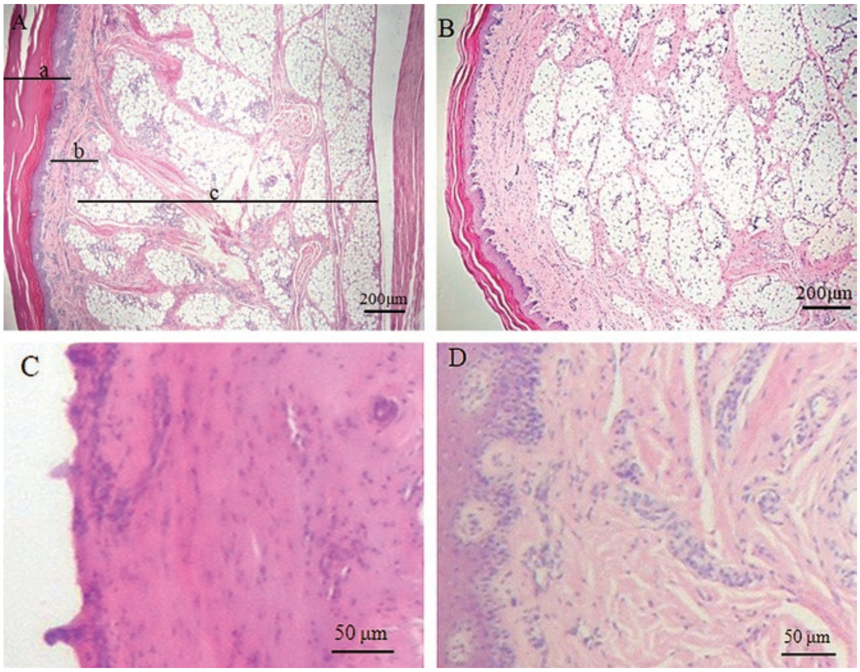

Fig. 2. The histological results of the paw pads. “A” is from No.1 cat fore paw pads; “B” is from No.2 cat hind paw pads. In the “A”, the “a” area is stratified epithelium, “b” area is dermis layer and “c” area is subcutaneous tissue layer. “C” is the high-magnified figure of the epidermis, the elliptical wireframe indicates granular layer and spinous layer. “D” shows the dermal papillae embedded in the stratified epithelium layer.

cats.

Contact strain experiment

The contact strain experiment in order to acquire the contact geometry information and contact strain information of the paw pads was done by using the Vic-2D (CSI VIC-2D, USA), which was an innovate system that used a non-invasive method called Digitized Image Correlation (DIC) technique. It used only one high-resolution couple charged device camera to capture the moving images of the subjects, and DIC tracked the gray distribution level in subsets of images of the specimen’s surface covered with natural contrast or painted random black-white speckle pattern to determine displacement and strain fields of the material under any type of loading. In the experiment, a glass plate was used as the substrate. After spraying speckle on the paw pads, the cats were allowed to move straight ahead on the substrate at various speeds, a high speed camera installed under the substrate captured the moving images, and the images were captured at 200 frames per second. The diagram of the experiment was shown in Fig.1 B and Supplemental Data.

Statistical method

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

Ethics statement

All procedures used in the animal experiments were approved by the Faculty of Veterinary Science Animal Ethics Committee of the Jiangsu University (No.19-0016).

Table 1. Material properties of all components used for model

Component	Element type	Young's modulus *E* (MPa)	Poisson's ratio
Stratified epithelium	3D tetrahedron	110	0.495
dermis layer	3D tetrahedron	10	0.450
subcutaneous tissue	3D tetrahedron	1	0.300
Ground plate	3D hexahedron	21300	0.300

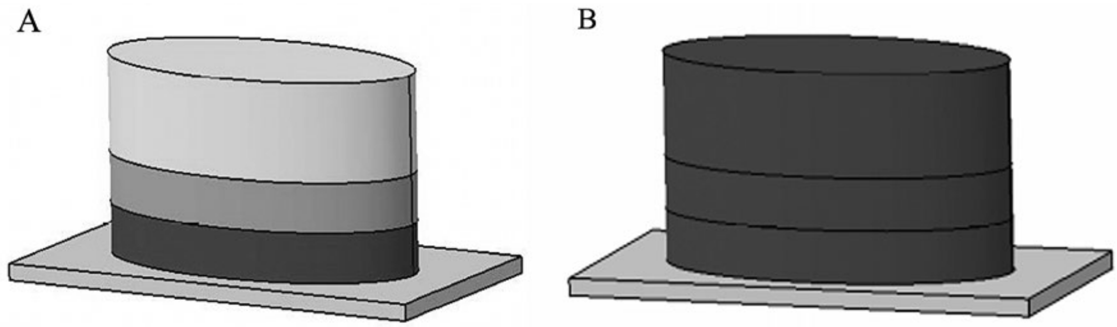

Fig. 3. Digital pad and uniform model. "A" is digital pad model and "B" is uniform model. The digital model consists of three layers, which simulate the three-layer structure of the digital pad respectively, and analyze the movement of the digital pad in contact with the ground.

Results

The histological experiment results

The histological experiment results of the two dead domestic cats' paw pads samples are shown in Fig.2 and Supplemental Data. By observing the histological results from the two cats, the main common point is that the tissue structure in superficial muscle can be divisible into three layers from outside to inside whether in front or hind paw pads: stratified epithelium layer, dermis layer and subcutaneous tissue layer. Among them, the components of the stratified epithelium layer are hard and can be divided into two parts: the corneum (red part in Fig.2 A a) mainly bears friction and impact during motion, and the non-corneum (purple part in Fig.2 A a), acts as a protective layer. Besides, the epidermis which is mainly made of stratified epithelium layer, also has some granular layer and spinous layer in outside of stratified epithelium layer, as can be seen in Fig.2 C; The dermis layer (pink part in Fig.2 A b) which is elastic in nature is mostly composed of dense connective tissue. And in the high-magnified dermis layer, as can be seen in Fig.2 D, some dermal papilla is embedded in the non-corneum of the stratified epithelium layer; The subcutaneous layer (in Fig.2 A c) is composed mainly of adipose tissue which shows the disordered network fiber structure. Besides, some dermal papillae and stratified epithelium formed by dermis have obvious mosaic structure on micro scale, which constitute the complete epidermis.

The histological finite element model analysis results

To clarify the function of the histological structure in cushioning characteristic, the digital pad model and uniform model are established based on the multi-layer structure characteristics of paw pad, as could be seen in Fig.3. The three-layer structure of the digital pad model have different material properties like the stratified epithelium layer, dermis layer and subcutaneous tissue layer respectively and their material properties are listed in Table 1[5,14], and the uniform model as a contrast model is unified as the material property of the stratified epithelium

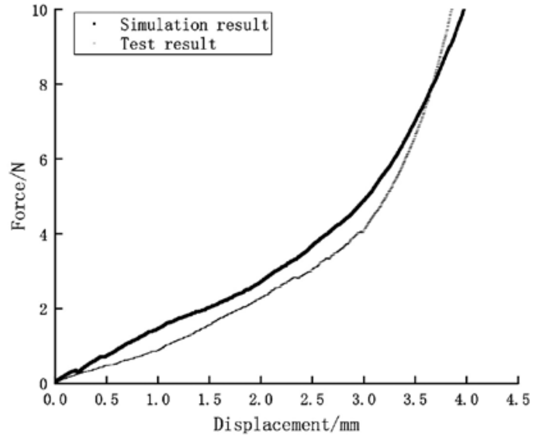

Fig. 4. Validation of the digital pad model. Through simulation and dynamic compressive experiment, the force-displacement curves under 10N loading are obtained and compared.

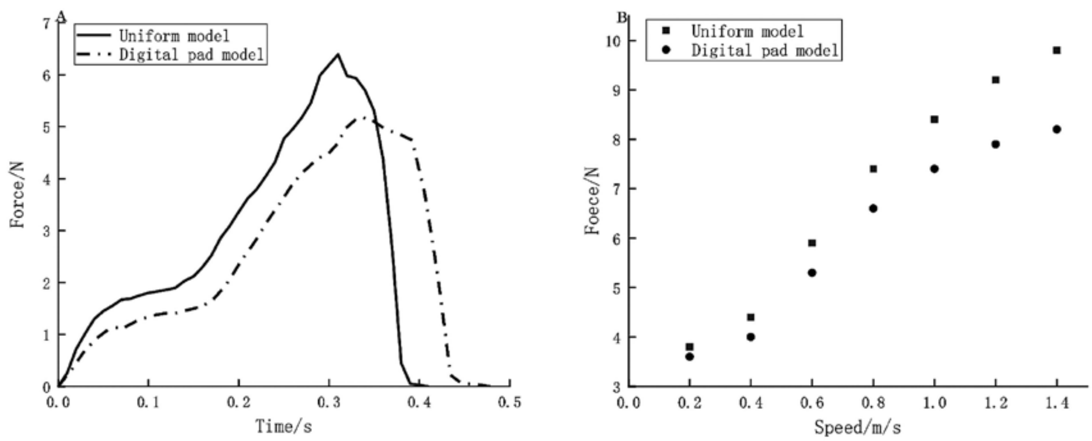

Fig. 5. The simulation analysis results of the two models. "A" was the result of grounding force of two models in the speed of 0.6m/s to collide with the ground. "B" was the results of grounding force of two models in the various speeds to collide with the ground.

layer.

The validity of the digital pad model is proved by comparing the simulation results with the experimental results in force-displacement, as shown in Fig.4, which showed the high fitting degree in simulation and test results of digital pad. After verifying the reliability of the model, the two models are simulated and analyzed in order to make them collide with the ground at the same initial velocity, and the grounding force during the impact process is obtained, and the speed range is from 0.2 to 1.4 m/s. As shown in Fig.5, is the grounding force distribution at speed of 0.6m/s and the comparison of the peak grounding force at different speeds of the two models. From the pictures, it is found that the ground force of digital pad model is significantly lower than that of the uniform model at the same speed, and the contact time was also longer than that in the uniform model benefited from multi-layer structure. Besides, with the speed increased the gap between the two models become more obvious.

The kinematic experiments results

GRFs experiment results

For the GRFs experiment, 256 groups data (16 groups data of each cat in fore and hind pads) about the GRFs of the domestic cats' paw pads within the experiment speed are acquired. By

Table 2. Comparison of the data between fore and hind paw pads of data (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**	
Site	Fore paw pads	Hind paw pads
Peak GRFs in paw pad /(%BW)	64.4±8.7	46.6±6.1
% of body distribution	52.2±1.8	47.4±1.6

Table 3. Comparison of the data between fore and hind paw pads in gaits of domestic cats

Gaits	**Peak GRFs in fore paw pads /(%BW)**					**Peak GRFs in hind paw pads /(%BW)**				
	2nd	3rd	4th	5th	M-pad	2nd	3rd	4th	5th	M-pad
Walking	8.7±1.1	11.7±1.8	14.6±2.3	10.9±1.3	37.2±4.4	3.9±0.6	10.2±1.7	12.1±1.5	8.3±0.9	25.1±3.2

statistical analysis of the acquired 256 groups of data, as shown in Table 2, it is evident that the peak GRFs of the fore paw pads are (64.4±8.7) percent of body weight and the peak GRFs of the hind paw pads were (46.6±6.1) percent of body weight. Besides, the parameter of the percentage of body distribution once again shows that the fore pads bear more peak GRFs than the hind pads. Differences were considered significant at $P < 0.05$ in the comparison data between the groups.

Furthermore, by observing the peak GRFs of digital pads and metacarpal pad for one whole paw, it could discover that the pads play a different role in the fore and hind pads. The domestic cats' paw pads can be divided into five areas: second pad (2^{nd}), third pad (3^{rd}), fourth pad (4^{th}), fifth pad (5^{th}) from the inside to the outside of the paw pad and metacarpal pad (M-pad). The GRFs of digital pads and metacarpal pad in fore or hind pad of one cat are shown in Fig.6. Comparing Fig.6 A and B reveal that when the gait speed is 0.65 m/s, the fore metacarpal pad bears more force with a longer grounding time than that of the hind metacarpal pad. Besides, for the four digital pads, in the fore paw pad, while they mainly bear the force in the later stage after the metacarpal pad is separated from the ground, but in the hind paw pads, they share the stress in the whole process. The peak GRFs of 3^{rd} pad and 4^{th} pad are much larger compared with 2^{nd} pad and 5^{th} pad. Similarly, through the statistical analysis of the data, the relevant results are shown in Table 3, which reveal the bearing capacity of each pads. Differences were considered significant at $P < 0.05$ in the comparison data between the groups.

Contact strain experiment results

Considering that, the forepaw pads of domestic cats play a more important in bearing GRFs under the experiment gait; thus, they are selected as the object to further explain the mechanism of the domestic cat's cushioning characteristic.

Based on the camera that captures the moving images of the cat's forepaw pads on the substrate, the data such as contact geometry information in per frames of the paw pads are acquired by processing the series of images with the DIC technique. As can be seen from the Fig.7 A, the stable contact geometry information of the paw pad is constructed in coordinate system and further, an accurate contact area data is also extracted. The stable contact area in different speed of fore and hind pads are shown in Fig. 7 B, it can be seen that, the stable contact area of the fore paw pad is larger than that in hind paw pad, and with the increase in speed, the stable contact area of the fore paw pad increases more obviously which may indicate the forepaw pads play a faster response with the gaits changed than hind paw pad.

With the help of the VIC-2D, the contact principal strain and its direction distribution

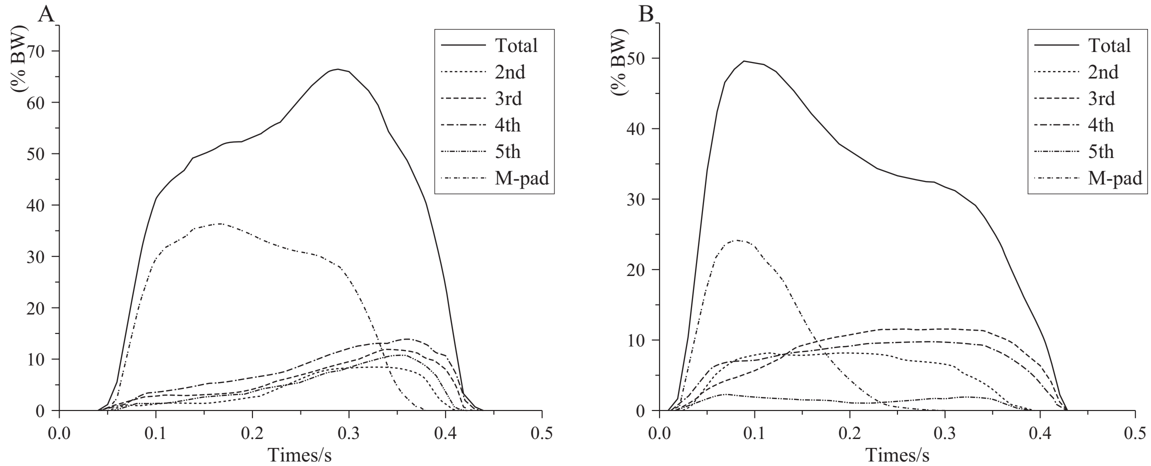

Fig. 6. The GRFs in fore and hind pads of one cat at speed of 0.65m/s. "A" is fore pad and "B" is hind pad.

field during the contact process between the paw pads and the ground are all obtained. As shown in Fig.8, takes the front paw pad of the cat at the speed in 0.78 m/s as an example which the X direction is the forward direction and the Y direction is the outside direction of the paw pad. Based on the results shown in Fig.8, it is found that the contact principal strain characteristics of the metacarpal pad are different from those of the four digital pads. On the one hand, in the direction distribution field, the four digital pads have basically no change in the whole contact process which mainly maintain the tensile deformation in Y direction; While in the contact time before 0.18 s, the metacarpal pad is tensile strain in Y direction, and in the rest contact time, it is mainly tensile strain in X direction. On the other hand, in the distribution of contact principal strain value, the four digital pads increase continuously in the whole process. As it can see that with the accumulation effect of strain effects in the Y deformation direction, the contact principal strain values of the inner edges of the 3rd and 5th digital pads increase from 6% to 15%, which becomes the maximum area of the digital pad. While for the metacarpal pad in the whole contact process, due to the change of strain direction, the strain value increases first and then decreases in the inner and outer regions alternately, and finally forms the main strain distribution feature with the back region of metacarpal as the main uniform deformation distribution. The maximum main strain value range is about 9%, which is obviously lower than the maximum main strain value of digital pad region by about 15%. The deformation characteristics of metacarpal pad can be divided into two stages: early adhesion stage and latter cushioning stage which caused by the friction force in the Y direction and is in order to better attach to the ground at adhesion stage and the direction of strain is adjusted by means of swing deformation to release accumulated strain energy and weaken local impact energy at cushioning stage.

In order to further clarify the effect of swing deformation in the metacarpal pad, the strain values in X and Y directions of the 3rd pad and metacarpal pad during the contact process shown in Fig. 9 are extracted. Comparison of Fig.9A and B shows that the strain values in X and Y directions of the 3rd pad are increasing because of its constant deformation direction during the contact process, while the strain values in X and Y directions of the metacarpal pad are not increasing because of the wobbling deformation effect. In addition, the strain values of metacarpal in the X and Y directions show fluctuation and opposite trend, that is, the strain value increased

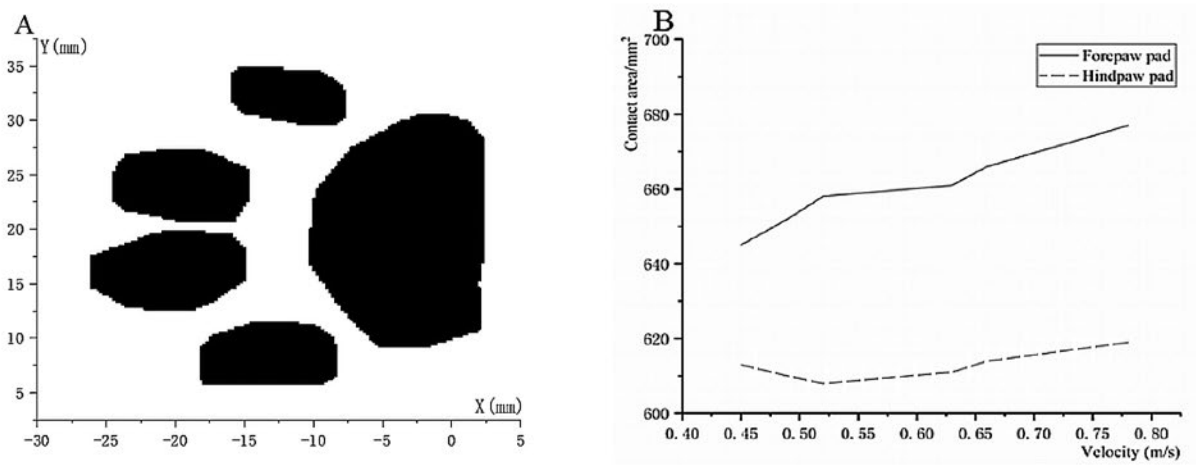

Fig. 7. The contact geometric information of paw pads. "A" is the stable contact geometry and "B" is the relationship between the stable contact area and speed in fore and hind paw pads.

or decreased in the X direction, and decreased or increased in the Y direction. Thus, the impact energy from the ground can be transformed into strain energy and dissipated in the alternate deformation of X and Y directions, so as to achieve the effect of cushion, which is better than that of four digital pad.

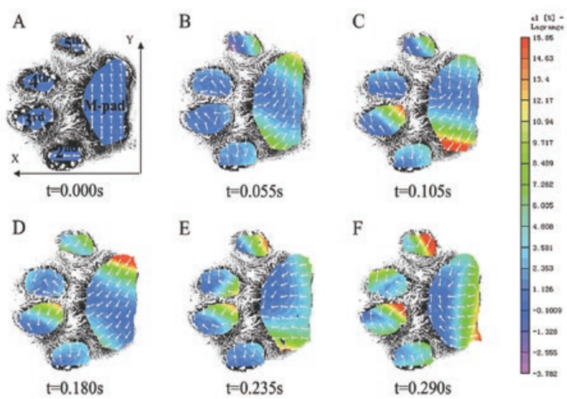

Fig. 8. Tthe contact principal strain and strain direction distribution in process. T_{total}=0.305 s, the "A"-"F" are the results of contact strain distribution characteristics with the time changed, and the value of the contact principal strain is in the form of LaGrange

Discussion

This is the first report that evaluating IA for dogs with CEA. Indocyanine green angiography revealed choroidal vessels which meandered through in the region coincided with choroidal hypoplasia, and it became clear that choroidal hypoplasia in CEA Hokkaido dogs also could be observed with IA in the area that could not be observed with simple funduscopy.

The histological characteristics of cat paw pads may be the internal factors that enable them to easily realize cushioning characteristic. The histological structure shows that paw pads are mainly composed of three layers is stratified epithelium layer, dermis layer and subcutaneous tissue layer, and it could prove that the multi-layer structure characteristics of the cat paw pad make it have nonlinear, visco-elastic properties and strong cushioning characteristics which benefited from the stratified epithelium layer, dermis layer and subcutaneous tissue layer's different material properties and their collaborative work to weaken the ground force. This similar structure also exists in the paw pad tissues of many other animals with good cushioning characteristics[7,10,11]. Similar descriptions in previous biomaterial experimental studies by El-Gendy and Rui Zhang record this kind of multi-layer structure of the paw pads able to achieve stress decay from outside to inside[6,23]. Specifically, the subcutaneous layer is composed mainly of adipose tissue which

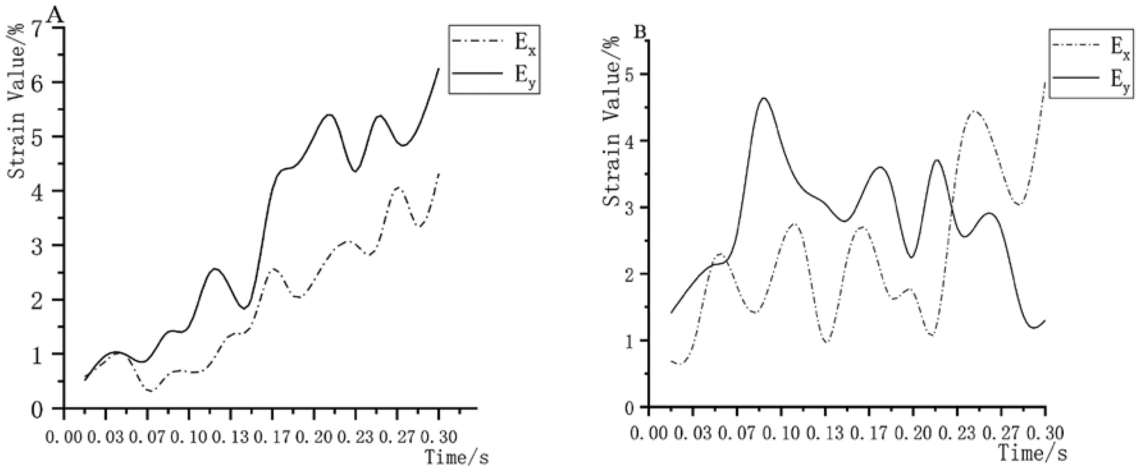

Fig. 9. The strain value of different pad regions in X and Y directions. "A" is the 3rd pad and "B" is the metacarpal pad.

shows the disordered network fiber structure. Adipose tissue is primarily full of adipocytes, which are separated by collagen membranes, whose mechanical behavior is considered to be equivalent to a hydrostatic system filled with incompressible fluid. Hence, the subcutaneous layer is composed of the softest material, which is the most important energy absorption layer in the three layers, and could effectively absorb vibration energy and reduce impact noise in the movement process[10,11]. Besides, it is worth mentioning that Huai-bin Miao[9] through a SEM experiment on dog paw pads finds that, the dermal papillae and the stratified epithelium layer, which have distinctive honeycomb-like structures at the micro-scale level, make up the structured epidermis layer and verification by finite element simulation shows that this layer can attenuate peak ground reaction-force more effectively. Indeed, these micro-structures, consisting of stratified epithelium and dermal papillae, have also been found in the paw pads of domestic cats. And it is also proved by Meyer W that through the enzyme and carbohydrate histochemical methods to study the eccrine tubular glands in the foot pad of the cat confirm the view that the normal biological functions of the eccrine glands of the feline foot pad are to improve the frictional capacities of the paw and gripping[15,16].

The histological structure of paw pads may reveal its natural advantage to realize the cushioning characteristics, and the kinematic mechanical characteristics in motion can be assumed that the acquired adaptive habits responsible for the realization of cushion characteristics[17,21,24,25].

The GRFs response of the fore paw pads is more sensitive in different gaits than that of hind, which also shows that the fore paw pads play a more critical role in the realization of biological characteristics. The contact gait of the domestic cats' paw pads is different from that of human or other plantigrade though they all undergo mechanical work by wobbling and deforming (damping spring effect)[26]. In humans, as suggested by Honert[9] in their work to unravel 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 contributed 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 fore sole contact landing process). By comparing the strain laws of contact strain distribution in X and Y direction, it is found that, the paw pad is able to achieve adhesion with the ground by producing the strain in Y direction, and achieve the cushion by producing the strain in X direction. As it can see, during the adhesion stage, the strain of paw pad mainly occurs in the Y direction, which indicates that the deformation in the Y direction is conducive to the formation of ground adhesion. When it is stable, the strain in the Y direction is basically unchanged. When it is in cushion stage, along with the trend of moving forward, the strain in the X direction is conducive to the transfer of strain and strain energy weakening in order to produce cushion effect. Finally, the response of the fore and hind pads to different degrees of bearing GRFs, as well as the adjustment of the contact principal strain distribution and strain direction of the paw pads in the contact process, is long-term habits to achieve the cushion characteristics.

Acknowledgments

We thank Ruituo Tech and Kang Chen for VIC-2D experiments. This work is supported by the National Natural Science Foundation of China (No. 52072156, No. 51675240 & No. 51605198) and Postdoctoral Foundation of China(2020M682269).

Supplemental data

Supplemental data associated with this article can be found, in the online version, at http://dx.doi.org/10.14943/jjvr.69.1.19

References

1) Alexander R, Bennett M, Ker R. Mechanical properties and function of the paw pads of some mammals. J Zool 209, 405-419, 1986.
2) Biewener AA. Biomechanics of mammalian terrestrial locomotion. Science 250, 1097-1103, 1990.
3) Boyd JS, Paterson C, Schnorr M, Schnorr B. Colour atlas of clinical anatomy of the dog and cat. Ferdinand Enke Verlag, 1995.
4) Chi K J. Functional morphology and biomechanics of mammalian foot pads. Durham: Duke University, 11-26, 2005.
5) Chi K J, Roth V L. Scaling and mechanics of carnivoran footpads reveal the principles of footpad design. J R Soc Interface 49, 1145-1155, 2010.
6) El GSAA, Derbalah A, El MMERA. Macro-microscopic study on the toepad of ostrich (Struthio camelus), Vet Res Commun 36, 129-138, 2012.
7) Erdemir A, Viveiros ML, Ulbrecht JS, Cavanagh PR. An inverse finite-element model of heel-pad indentation. J Biomech 39, 1279-1286, 2006.
8) Fontanella CG, Forestiero A, Carniel EL. Analysis of heel pad tissues mechanics at the heel strike in bare and shod conditions. Med Eng Phys 35, 441-447, 2013.
9) Honert EC, Zelik KE. Foot and shoe responsible for majority of soft tissue work in early stance of walking. Hum Mov Sci 64, 191–202, 2019.
10) Huaibin M, Jun F, Zhihui Q. How does the canine paw pad attenuate ground impacts? A multi-layer cushion system. Biol Open 6, 1889-1896, 2017.
11) Hubbard C, Naples V, Ross E. Comparative analysis of paw pad structure in the clouded leopard and domestic cat. Anat Rec 292, 1213-1228, 2009.
12) Karen MK, Adam G, Ann F. Segmental foot and ankle kinematic differences between rectus, planus, and cavus foot types. J Biomech 94,180-186, 2019.
13) Ker RF. The design of soft collagenous load-bearing tissues. J Exp Biol 202, 3315-3324, 1999.
14) Leyva-Mendivil M F, Page A, Bressloff N W. A mechanistic insight into the mechanical role of the stratum corneum during stretching and compression of the skin. J Mech Behav Biomed Mater 49, 197-219, 2015.
15) Meyer W, Bartels T. Histochemical study on

the eccrine glands in the foot pad of the cat. Basic Appl Histochem 33, 219-38, 1989.
16) Meyer W, Bartels T, Tsukise A, Neurand K. Histochemical aspects of stratum corneum function in the feline foot pad. Arch Dermatol Res 281, 541-543,1990.
17) Mirela RV, Sheila CR, Felipe SA. Kinetic and temporospatial parameters in male and in male and female cats walking over a pressure sensing walkway. BMC Vet Res 9,129-137, 2013.
18) Motoshi K, Tim RL, Walter H. Control of ground reaction forces by hindlimb muscles during cat locomotion. J Biomech 39, 2752-2766, 2006.
19) Natali AN, Fontanella CG, Carniel EL. Constitutive formulation and analysis of heel pad tissues mechanics. Med Eng Phys 32, 516-522, 2010.
20) Qian Z, Ren L, Ren L. A coupling analysis of the biomechanical functions of human foot complex during locomotion. J Bionic Eng 7, S150-S157, 2010.
21) Qian ZH, Miao HB, Shang Z, Ren Luquan. Foot-ground contact analysis of German shepherd dog in walking, trotting and jumping gaits. Journal of Jilin University (Engineering and Technology Edition) 44, 1692-1697, 2014.
22) Robert JG, Judith LS, Dagan WS. Hindlimb Kinetics and Neural Control during Slope Walking in the Cat: Unexpected Findings. J Appl Biomech 17, 277-286, 1997.
23) Rui Z, Lei L, Dianlei H. FEM analysis in excellent cushion characteristic of ostrich (Struthio camelus) toe pads. PloS One 5, 1-24, 2019.
24) Rumph PF, Lander JE, Kincaid SA. Ground reaction force profiles from force platform gait analyses of clinically normal mesomorphic dogs at the trot. Am J Vet Res 55, 756-761, 1994.
25) Tian WJ, Cong Q, Jin JF. Joint angles and ground reaction force of German shepherd dog. Journal of Jilin University (Engineering and Technology Edition) 39 (S1), 227-231, 2009.
26) Whittle MW. Generation and attenuation of transient impulsive forces beneath the foot: a review. Gait Posture 10, 264-275, 1999.
27) Zhang XP, Yang JL, Yu H. Mechanical buffering characteristics of feline paw pads. J Biomed Eng 29, 1098–1104, 2012.