Journal of Veterinary Behavior 10 (2015) 248–254

Contents lists available at ScienceDirect

Journal of Veterinary Behavior

journal homepage: www.journalvetbehavior.com

In Brief: Practice and Procedure

# Developing biorobotics for veterinary research into cat movements

Chiara Mariti [a,*], Giovanni Gerardo Muscolo [b], Jan Peters [c,d,e], Domenec Puig [f], Carmine Tommaso Recchiuto [b], Claudio Sighieri [a], Agusti Solanas [f], Oskar von Stryk [c]

[a] *Dipartimento di Scienze Veterinarie, Università di Pisa, Pisa, Italy*
[b] *CVD & E-I Laboratories, Humanot s.r.l., Prato, Italy*
[c] *Department of Computer Science, Technische Universität Darmstadt, Darmstadt, Germany*
[d] *Department of Empirical Inference, Max Planck Institute for Intelligent Systems, Tübingen, Germany*
[e] *Department of Autonomous Motion, Max Planck Institute for Intelligent Systems, Tübingen, Germany*
[f] *Department of Computer Engineering and Mathematics, Universitat Rovira i Virgili, Tarragona, Spain*

ARTICLE INFO

*Article history:*
Received 8 April 2014
Received in revised form
29 September 2014
Accepted 31 December 2014
Available online 10 January 2015

*Keywords:*
3Rs
biorobotics
cat
gait analysis
locomotion
noninvasive

ABSTRACT

Collaboration between veterinarians and other professionals such as engineers and computer scientists will become important in biorobotics for both scientific achievements and the protection of animal welfare. Particularly, cats have not yet become a significant source of inspiration for new technologies in robotics. This article suggests a novel approach for the investigation of particular aspects of cat morphology, neurophysiology, and behavior aimed at bridging this gap by focusing on the versatile, powerful locomotion abilities of cats and implementing a robotic tool for the measurements of biological parameters of animals and building cat-inspired robotic prototypes. The presented framework suggests the basis for the development of novel hypotheses and models describing biomechanics, locomotion, balancing system, visual perception, as well as learning and adaption of cat motor skills and behavior. In subsequent work, the resulting models will be tested and evaluated in simulated and real experiments and validated with specific experimental data gathered from cats. This methodology has application in several areas including dynamic models and artificial vision systems. From an ethical point of view, this approach is in line with the 3R principles: the detailed and integrated systems will allow us to study a small number of cats (reduction) for the implementation of noninvasive tools such as electromyography and gaze analysis (refinement), which will make the construction of a substitute to experiments on living cats (replacement) easier. For instance, bioinspired prototypes could be used to test how specific visual and physical impairment in cats (up to partial or total blindness, loss of a leg, and so forth) change their walking and jumping abilities. This modus operandi may pave the way for a new generation of research in the veterinary field. Moreover, the measurement tools to be developed will constitute an achievement per se as for the first time visual, muscular, and gait analysis of cats will be integrated, and this will help to improve the rehabilitation procedures for cats and other nonhuman animals.



## Introduction

Biorobotics can be defined as the intersection of biology and robotics (Webb, 2001). Research involving bioinspired and biomimetic models has become increasingly relevant to both biology and engineering, with applications to industrial design. In particular, over the past decade the use of bioinspired robotic models in biological research has been rapidly increasing for various reasons. From a biological perspective, robotic prototypes modeling living systems perform 2 major functions: validation of a conceptual understanding of physical, behavioral, and sensomotoric processes (Long et al., 2006; Lauder et al., 2007; Phelan et al., 2010) and exploration of biological parameter spaces (Doorly et al., 2009). Physiological systems can be replicated using biorobotic structures that attempt to match their functional materials, structural, mechanical, electrical, and fluidic properties. Once a suitable model has been established, it can be used to address numerous

All the authors contributed equally to the study.

* Address for reprint requests and correspondence: Chiara Mariti, Dipartimento di Scienze Veterinarie, Università di Pisa, viale delle Piagge, Pisa 2-56124, Italy.
*E-mail address:* cmariti@vet.unipi.it (C. Mariti).

http://dx.doi.org/10.1016/j.jveb.2014.12.010
1558-7878/

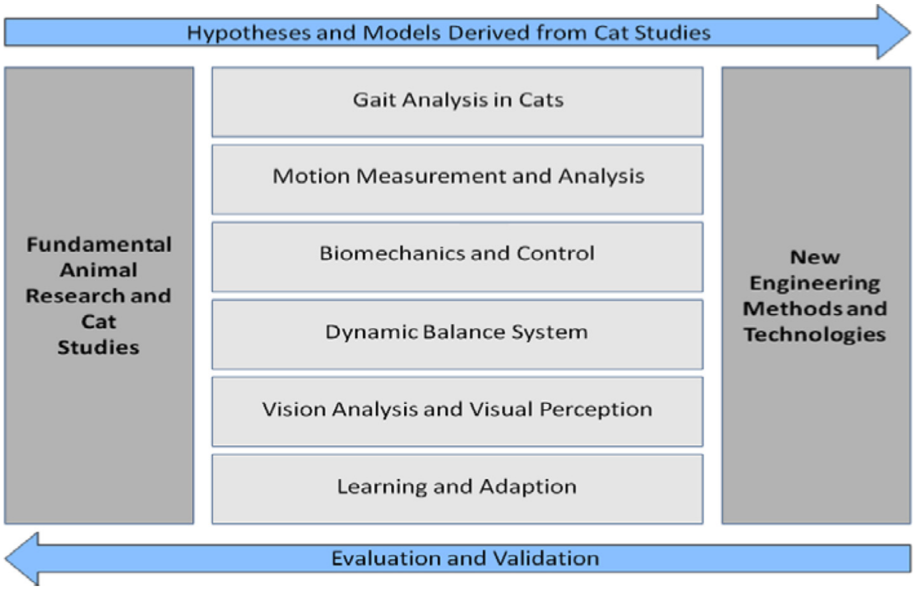


**Figure 1.** Scheme of the proposed approach.

scientific questions, some of which would be nearly impossible to investigate by solely relying on a living biological organism, repeatedly performing the analyzed behavior.

With the appropriate robotic prototype, scientists can replicate the desired kinematic pattern and examine the motion in simplified terms (Phelan et al., 2010) or produce a motion that fills a parameter space that cannot be observed under normal conditions (Long, 2007). Such an approach has already been used for swimming (Richards and Clemente, 2012) and flying (Lehmann et al., 2010) of animals and for human walking (Seyfarth and Geyer, 2002), running, and jumping (Radkhah et al., 2011).

The synergies between different professionals (e.g., biologists, veterinarians, computer scientists, and engineers) emerge during the construction of bioinspired and biomimetic robotic prototypes. The importance of veterinarians in all stages of such studies is obvious, as this professional has the crucial role of planning, monitoring, and interpreting research results involving animals, and similarly important, veterinarians are in charge of animal welfare protection.

Animal experiments are often associated with pain, fear, and/or suffering and do not directly benefit the research animal (Rusche, 2003). In the United States, more than 20,000 cats are annually used for research, and almost half of them are involved in research causing them pain (United States Department of Agriculture, 2010). Hence, many animal welfare associations demand the immediate abolition of all animal experiments, whereas from the perspective of those who allow animal experiments, the benefits of the research outweigh the animal suffering. To alleviate this situation, one of the focal points of veterinary and biology research should be the establishment of novel technologies and ethical procedures that reach the same scientific goals, while using fewer animals, reducing their suffering, or without using animals at all. These are the so called 3R principles: (replacement, refinement, and reduction; Russell and Burch, 1959). Robotics can be an extremely convenient tool to attain this aim. The symbiotic interaction of robotic technologies with veterinary and biology researchers has recently been shown to yield good results (Holmberg and Pelletier, 2009).

In this article, we describe a novel approach combining robotics and veterinary research, a long-term vision that depicts the use of novel robotic devices as substitutes for real cats in neurophysiological studies, thereby avoiding surgical modifications and the consequent impairment of cats. We propose a replacement technology that is completely noninvasive for the measurement of biological parameters and to develop cat-inspired robotic prototypes. Such prototypes could provide both the capability to execute realistic complex motions as well as full knowledge over cat egomotion, significantly aiding complementing research by evaluating and validating hypotheses and models derived from cat studies and, finally, probably even becoming a substitute for living cats in behavioral and neurophysiological experiments. It should be noted that the development of cat robot prototypes with such muscular-skeletal functionality and behavioral capabilities will also significantly advance the state of research in robotics.

Until now, research on cat locomotion has required invasive monitoring and/or the experimental impairment of cat functional structures. We propose a novel paradigm for the behavioral, neuroscientific, kinematic and dynamic analysis of cats (Figure 1). A new complementary set of integrated measurement tools should be used to monitor the physiological parameters of interest following a noninvasive approach; in particular, techniques can be adapted for the measurement of electromyographic (EMG) signals and gaze and head movements. A novel, noninvasive cat motion measurement and analysis tool that integrates multimodal data obtained from external and on-body measurements needs to be developed. The monitoring of these parameters, together with the analysis of all jumping and landing forces, and a reconstruction of the body movements by a motion capture system will provide the basis for a deepened understanding and modeling of the behavioral and sensomotoric abilities and control architecture that can be translated into design guidelines for the development of novel robotic cat prototypes.

These bioinspired robotic prototypes will open up a wide amount of novel possibilities for robotics as well as veterinary research in full compliance with the 3R principles. Prototypes will also allow researchers to test whether and how specifically visual and physical impairment in cats (up to partial or total blindness, loss of a leg, and so forth) modify their abilities to walk and jump, without using live animals. Moreover, we aim also to investigate technologies for noninvasive EMG and gaze analysis that can open new ways in veterinary practice for the benefit of the research and animals.

## Methodology: integrated noninvasive measurement environments

### *Direct observation*

The proposed approach starts with the direct observation of real cats and the collection and analysis of new types and quantity of data that provide the basis for the establishment of the robotic prototype. In the first phase, a small group of privately owned house cats will be involved in the research, with their owners' consent. The cats will be trained humanely to habituate them to the designed experimental room, to the maze, and to the equipment needed for the investigations. The habituation phase will be carried out and monitored by veterinarians expert in animal behavior.

Refinement can be defined as those methods that avoid, alleviate, or minimize the potential pain, distress, or adverse effects suffered by the animals involved or which enhance animal well-being (Morton, 1997). Therefore, the participation of a veterinarian expert in animal behavior could be regarded as a refinement action in research, that is, a further action promoting animal welfare protection: They have the knowledge and skills to both assess and reduce stress in animals, including that caused by the social and physical environment.

The experimental room will have an empty space and a maze where cats will be able to move freely while enabling new multimodal measurements. The 2 scenarios will allow us to analyze the biomechanics, kinematics, and dynamics in cats walking in different conditions (empty space, avoiding a low, high, or side obstacle, turning with angles of different degrees, and so forth) and in cats jumping up at and down from different heights. These data will define the basic mechanical abilities of the robotic cat. After the training period, cats will be noninvasively monitored while walking and jumping through the measurement and analysis tools that will be developed in parallel.

This approach aims at obtaining an integrated gait analysis that will allow obtaining experimental insights on the perceptive, sensomotoric, and control mechanisms underlying regular locomotion in cats. The type of experiments and measurements will be adapted to meet the needs of the robotic prototype design for the model development and validation.

During the jumping and the landing phases, reflective markers on cat body will be used as external measurements using high-speed video cameras. The markers can be fixed in particular areas to analyze specific data about jumping motions (e.g., spine, head, and tail). Use and potential benefits of additional complementary external sensors like 'lidars' (light detection and ranging measurement system) can be investigated. To minimize errors caused by skin marker movements, the location of the knee joint centre (and other relevant joints) can be determined using an optimization procedure, in which the estimated location of the knee joint centre will be optimized to be the one closest to the measured location of the knee marker, with the constraint that the distances from the estimated knee joint centre to the measured ankle and hip joints will be the same as the measured shank and thigh lengths, respectively.

These measurements of body kinematics are integrated with movement data consisting of ground reaction forces of the instrumented hind limb that will measure impact using a force platform and stored simultaneously with the marker images. These data can be interpreted using validated models of motion dynamics and balancing together with data from a novel body area network consisting of on-body sensors (accelerometers, gyroscopes), noninvasive EMG measurement systems, and an eye-head position tracker. In this way, functional principles in cats on the level of actuation and control of their musculoskeletal apparatus can be investigated, which is a necessary and essential prerequisite for the design of the intended robotic cat. Special attention must be paid to the simultaneous recording of the different data with synchronized time stamps. Mazes and obstacles in the environment can be present (they will be transparent or open at the top for marker-based motion capture systems). In addition, possible implementations of further active elements (e.g., monitors, speakers, systems releasing objects) can be investigated.

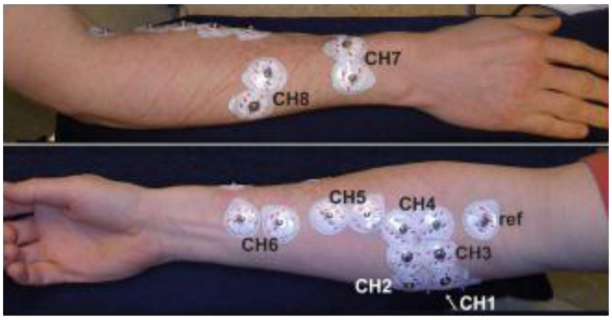


**Figure 2.** Noninvasive electromyograph applied to humans (Biedermann et al., 2000).

Moreover, some aspects related to the environment and learning procedures, such as the possible effects of repetition of exercises and rewards (goal-oriented vs. casual walking, and jumping to catch a hanging prey-like toy vs. jumping to reach a high place), can be examined as well.

### *EMG measurements*

The electromyogram is a graphic record of the contraction of a muscle as a result of electrical stimulation. EMG is the preparation, study, and interpretation of electromyograms.

The standard way to implement this kind of a test is by means of an invasive procedure that involves the usage of needles. Recently, novel noninvasive technologies have been tested and used with human subjects (Biedermann et al., 2000; Figure 2). The main problem of a noninvasive methodology is the low level of the signal-to-noise ratio, which usually does not allow reliable data to be collected.

Sebelius et al. (2006) proposed and described a myoelectric control system for prostheses based on an EMG recording setup comprising 8 bipolar EMG amplifiers with a 10 Hz analog high-pass filter. This setup will allow an investigator to obtain an amplification of up to 5000 times, using disposable bipolar EMG electrodes with an interdistance of 22 mm center to center, a 6-order Infinite impulse response (IIR) Butterworth filter to eliminate the power line noise, and an 11-order IIR low-pass filter (Chebyshev) with a pass frequency of 800 Hz to attenuate higher frequency noise. This experimental setup was used to successfully control a virtual hand and later a real hand (Cipriani et al., 2009). Such noninvasive methodologies have not been used with animals sufficiently. Some procedures are described as minimally invasive, but they still involve the use of subcutaneous implants, both arm mounted and cranial mounted (Biedermann et al., 2000; Hudson et al., 2010). With the current approach, it will be possible to investigate if there is a possibility to use a completely noninvasive EMG in animals such as cats.

Moreover, it is plausible that this approach and the resulting insights could be easily translated to other animals of comparable size.

### *Gaze analysis*

A novel eye-head position tracker (head-mounted camera plus eye camera with dichroic mirror) can be developed with respect to the hypotheses and models developed analyzing the visual

**Figure 3.** The eye-tracking equipment for dogs developed by Williams et al. (2011).

perception of real cats and their interconnection with motion control. An inspiration for the development of such device is the work of Williams et al. (2011) (Figure 3). They worked on a mobile, head-mounted, video-based, eye-tracking system for dogs. This setup allows for free movement of the dogs while being completely noninvasive (assuming that the animal has been appropriately habituated to the equipment). It should be possible to adapt this technology to free-moving cats by using a head-mounted eye tracker and a scene imager (consisting of a scene camera, an eye camera, an infrared light source, and a dichroic mirror). It is expected that this system will be able to collect pupil size, eye movement, and eye point of regard data while allowing complete freedom of head movement. The system has been successfully tested on dogs, as well as on smaller animals such as lemurs (Shepherd and Platt, 2006). The weight of the system should not inhibit successful measurements of gaze behavior during spontaneous locomotion in cats.

Furthermore, a complementary external vision system, which performs segmentation and tracking of the head of moving cats and analysis of the head oscillations, should be investigated. By tracking the cat's head, it should be possible to measure the oscillations and how the eyes adapt to them. The use of infrared cameras (as widely used in human-computer interaction studies) to determine, in a noninvasive way, the movement of cat eyes in the presence of external moving stimuli can be studied. The goal of this approach is to yield accuracy while being noninvasive. Thus, infrared cameras will be used and not be placed on the cat, but in front of the cat. A set of images can be projected on a screen (e.g., pictures of mice) whereas the cat's eye movements can be tracked by the infrared cameras mounted above the screen. A vision system with multiple cameras can be used to track and analyze the visual attention system of cats in motion.

## Robotic prototype

The proposed approach aims at a fundamentally new way to understand the functional principles underlying the behavioral, locomotor, perceptual, and sensomotoric abilities of cats that represent supremely efficient muscular machines in their ability to jump, twist, and turn with a ratio of their strength to their size far superior to humans.

One of the aspects of this novel approach is represented by the development of a robotic prototype able to reproduce some peculiarities of cats. In our vision, the specifications and the engineering requirements for the definition of a complex robot will be derived from the analysis conducted on real cats, by means of the novel integrated noninvasive measurements environment. However, some basic concepts and fundamental aspects of the robotic prototype, needed to imitate the cat motion and behavior, have already been defined and analyzed and they will be here summarized.

### *Biomechanical models*

Novel and improved biomechanical models of the locomotor system of cats need to be developed. They serve for multiple purposes such as: (1) model-based analysis and investigation of hypotheses based on the multimodel data provided by the novel integrated noninvasive measurement environment; (2) the engineering design of a robotic cat prototype; (3) the development of model-based methods for control and perception of the robot. Two categories of models need to be considered (Full and Koditschek, 1999). A template is a pattern that describes and predicts the behavior of the animal's body in pursuit of a goal. Conceptual models account only for as few as necessary details of joints, muscles, and neurons. They typically consist of only 1 or a few masses and mostly mass less compliant limbs and spine, for example, spring-loaded inverted pendulum (SLIP) models (Geyer et al., 2006). Such conceptual models are very helpful for investigating the relation between motion and behavior control of the cat and the actual actuation and control on joint level. They are also needed for developing corresponding abilities in the robot prototype. An anchor describes a more elaborated and more physically realistically multibody system dynamics model (MBS) (Schiehlen, 1997) up to the level of joints and muscles. Musculoskeletal MBS dynamics models are highly complex, and their validation will strongly depend on the success of the development and application of noninvasive, wireless, on-body EMG measurements of the main muscle groups of cats. Published reference data of the cat anatomy will have to be used as the initial bases for the MBS model parameters, especially for highly reliable data such as typical lengths and orientation of segments. The respective model parameters will then be estimated on the basis of the experimental measurement data using nonlinear optimization techniques. On the basis of the experimental data, the novel forward and inverse kinematics and dynamics models of the biomechanics of the cat can be developed and applied to account for the elastic actuation of the musculoskeletal system and the elastic spine function. Proprioceptive feedback control loops can be investigated as the basis for motion control and stability. These models will serve to obtain new insights from the perspective of animal research into the principles underlying the abilities of the cat that can be validated by experimental data and to assist the analysis of measured data related to cat's gait and jumping motions by inverse dynamics simulation using a biomechanics MBS dynamics model.

### *Compliant actuation and locomotor system*

Lightweight and powerful, compliant actuation of joints of the robotic prototype with a comparable range of elasticity and damping required to achieve cat locomotion abilities, for example, in jumping, imposes a great challenge for robot design and development. Most legged robots still use stiff joint actuation with only very limited abilities to store energy passively to support push off for the next step or to compensate for shocks from collisions of the feet with the ground. Only very recently the development of new variable impedance actuators with such properties has gained strong momentum in robotics (Vanderborght et al., 2013), which provide promising abilities for compliant robot design. The development of actuation for the cat robot prototype requires the use of the previously developed MBS dynamics models to investigate different design variants including compliant actuation on joint level only versus tendon-driven series elastic actuation implementing functional effects of biarticular muscles on locomotion (Radkhah et al., 2011). Furthermore, only few previous works have addressed research and development of a proper flexible robot spine (Seok et al., 2013), which is of high importance to achieve highly dynamic cat locomotion.

*Locomotion control for multiple gait types*

A number of results have been obtained so far to achieve specific 4-legged gaits in 4-legged robots with compliant legs (e.g., Spröwitz et al., 2013). However, the large versatility in gaits and locomotion as demonstrated by cats (e.g., walking, running, jumping, and climbing) has not yet been possible to develop in a 4-legged robot. Even developments enabling "natural" walking, trotting, and running motions in 1 robot design, which can move freely and is not constrained by passive holding mechanisms, has not yet been solved. The common approach to improve and extend common postural stability in walking control can be defined by investigating solutions oriented to bypass the concept of the zero moment point control (Vukobratović and Borovac, 2004; Muscolo et al., 2011; Muscolo et al., 2014). Zero moment point–based approaches are still commonly used in humanoid and animaloid robotics but cannot be applied for running and jumping abilities.

The investigated novel models for biomechanics (kinematics and dynamics) of cat locomotion with different levels of detail ranging from conceptual template models (such as SLIP models) to more detailed anchor models (elastic MBS dynamics models resembling a musculoskeletal model of the cat body in silicone) can be studied to account for the high elasticity in limbs and spine. On the basis of these models, cost functions related to the control of different cat motions (considering kinetic and potential energy vs. speed and jumping height) can be investigated providing further, new insights. From these measurements, performance specifications could be derived for the requirements of variable elastic actuation on joint level to achieve cat-like motion performance in robots. Neuromuscular models and reflexes, as investigated by Geyer and Herr (2010), are expected to play a relevant role in improving stability and robustness of dynamic locomotion patterns.

*Jump strategy*

The jump technique, consisting of a very deep crouch or a liftoff of the forelimbs followed by an explosive extension of the hind limbs, can also be investigated. Two primary phases of jumping are defined based on the hind limb kinematics: the preparatory phase, defined from the liftoff of the forelimbs until first ankle extension, and the propulsive phase, defined from first ankle extension to the end of paw contact. There exists a relationship between maximum takeoff velocity and several carefully chosen morphologic and physiological traits in domestic cats. Variation in cat maximum takeoff velocity is explained by both hind limb length and fat mass relative to lean body mass, but not by extensor muscle mass relative to lean mass or fast-twitch fiber content. The high performance requirements to meet the jumping ability of cats require proper use of mechanical elasticity in the actuation for storing and releasing energy. Moreover, the functionality of the cat-compliant body morphology is crucial for its motion performances, for example, the flexible spine for jumping, but it has not yet been well analyzed and modeled.

*Proprioception and vestibular system*

The ability to plan and control motions requires proper sensing of joint positions as well as accelerations and tilt angular velocities of the quadruped that can be achieved by proper state-of-the-art robotic sensors.

*Dynamic balance system and reflexes*

Cats have an exceptional sense of balance, easily wandering along high and narrow spaces. For implementation of such a balance system in a robotic prototype, proprioception sensors (e.g., touch, accelerometers, strain gauges) and exteroception sensors (e.g., force sensors) will be considered as internal sensors, along with its integration with the vision system.

A dynamic evaluation of the robot posture by means of control of the effective position of the centre of mass of the system, also when the system is in the air, will be one of the key elements to derive and test the balance model. The balance architecture will consider an extension of the recently proposed virtual pivot point control based on a SLIP model (Maus et al., 2010). This controller stabilizes the torso by applying a hip torque such that the ground reaction force is directed at a fixed point on the torso, the virtual pivot point, above the centre of mass. The adopted model to implement the control will consider conceptual models like a quadrupedal SLIP with rigid trunk with a certain deflection and elasticity. SLIP and related models are an effective way for studying fundamental principles in running and jumping motions of animals and robots.

*Vision system*

The cat visual apparatus is its most relevant exteroceptive sense for perception of the environment with respect to locomotion and also presents many interesting characteristics. Cat vision detects even the smallest movements; it is better suited for close-range objects, and it focuses on the center of what their eye observes. These features are helpful for concentrating on small preys. Just as humans, cats have a large binocular vision that allows them to perceive scenes as 3-dimensional images and provides them with a useful distance judgment and depth perception. For cats, visual guidance is often critical during locomotion (Fowler and Sherk, 2003), especially for motion planning. The vision of a moving cat is made up of many short constant gazes, fixed relative to their bodies or heading point, alternating with frequent shifts. If a walking cat maintains an angle of gaze that is constant relative to his body, retinal image motion will resemble Gibson's optic flow field, called travelling fixation (Fowler and Sherk, 2003; Patla and Vickers, 1997). The latter seems to primarily allow cats to acquire visual information about heading and velocity; it occupies most of the time, but it is frequently alternated with gaze shifts. Only rarely does a moving cat fixate and track a stationary feature of the environment (Fowler and Sherk, 2003). Tracking during locomotion varies with the complexity of the task, the presence of an obstacle leading to increased frequency and duration of sampling. Interspersed with the periods of travelling fixation, subjects saccade to the obstacle and presumably integrate the information gained on the location of the object with the proprioceptive and visual information concerning locomotion.

A new tracking methodology needs to be developed for analyzing and modeling the ability of cats to compensate head oscillations during their motion that inertially stabilize the vision system while allowing to assess the way in which cats perform visual tracking, including major reflexes such as the vestibular-ocular reflex and saccadic movements. This methodology will be based on determining the optical flow through a discontinuity-preserving filtering stage based on tensor voting instead of the commonly used Gaussian filtering based on structure tensors. In this way, the new designed approach aims at overcoming the drawbacks of current techniques such as undesired sensitivity to noise, undesired blurring of discontinuities, and undesired loss of accuracy in the resulting flow fields. The extraction of key computer vision features provides the basis for investigating a novel kinematic or dynamic model of the cat vision system.

### *Adaption and learning*

Regarding learning and adaption of motor skills, a novel methodology for automatic generation of robotic cat locomotion and jumping behavior from real cat behavioral data based on the musculoskeletal properties of the cat body needs to be developed. Methods for data-driven determination of the relation between cat jumping behavior and other characteristic types of locomotion and its environment as well as body impairment can be developed and applied. Cats (like other mammals) can control fast motions of their body with high performance despite their highly elastic body properties. As the latency of visuomotor and vestibulomotor commands is more than 50 ms for cats (Ghez and Vicario, 1978), it is likely that high-speed control is feedforward. To account for these in feedforward control of fast motions, methods for using and adapting motion dynamics models in motor learning and control need to be developed.

Testing for both regular locomotion and extreme jumping in simulation can occur. Validation is based on physical robotic prototypes for regular locomotion, including walking and jumping, as well as on predicting real cat behavior using cloned behavior policy and by predicting cat impairment from behavioral data.

## Conclusions

This article introduces a novel approach for the investigation of functional principles underlying cat morphology, locomotion, sensing, perception, behavior, and control. The proposed approach consists of the development of a novel noninvasive measurement environment providing multimodal data by monitoring cat behavior and locomotion in a coherent and systematic manner using external tracking and on-body sensors. This novel measurement environment is expected to provide new insights on biomechanics, perception, motion, and behavior control, as well as on learning and adaption principles in cats. The resulting functional and structural insights pave the way for new research in robotics, leading to the development of novel technologies for developing a cat robot prototype. With this robotic prototype, these new and improved findings as well as hypotheses on cats can be validated. Finally, it may lead to the replacement of experiments with living cats by experiments with the cat robot prototype. Therefore, we expect that a new modus operandi implementing this approach could have a wide impact; indeed, this new paradigm can open new ways in robotics, improving the performance of robots in terms of locomotion and adaptability, with the investigations on novel dynamic balance models and artificial vision system. In a long-term vision, robotic devices can be seen as substitutes for real cats in neurophysiological experiments. In addition, the implementation of noninvasive tools for the measurement of cat physiological parameters may be beneficial in veterinary practice and therefore for the treatment of animals and for animal welfare.

## Acknowledgment

The authors thank the veterinarian Dr. Romy Choueri for helping in the definition of the idea.

## References

Biedermann, F., Schumann, N.P., Fischer, M.S., Scholle, H.C., 2000. Surface EMG-recordings using a miniaturised matrix electrode: a new technique for small animals. J. Neurosci. Methods 97, 69–75.

Cipriani, C., Antfolk, C., Balkenius, C., Rosen, B., Lundborg, G., Carrozza, M.C., Sebelius, F., 2009. A novel concept for a prosthetic hand with a bidirectional interface: a feasibility study. IEEE Trans. Biomed. Eng. 56, 2739–2743.

Doorly, N., Irving, K., McArthur, G., Combie, K., Engel, V., Sakhtah, H., Stickles, E., Rosenblum, H., Gutierrez, A., Root, R., Liew, C.W., Long, J.H., 2009. Biomimetic Evolutionary Analysis: Robotically-Simulated Vertebrates in a Predator-Prey Ecology. Proc. 2009 IEEE Symposium on Artificial Life. Nashville, Tennesee, USA; p. 147-154.

Fowler, G.A., Sherk, H., 2003. Gaze during visually-guided locomotion in cats. Behav. Brain Res. 139, 83–96.

Full, R.J., Koditschek, D.E., 1999. Templates and anchors: neuromechanical hypotheses of legged locomotion on land. J. Exp. Biol. 202, 3325–3332.

Geyer, H., Herr, H., 2010. A muscle reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities. IEEE Trans. Neural. Syst. Rehabil. Eng. 18, 263–273.

Geyer, H., Seyfarth, A., Blickhan, R., 2006. Compliant leg behaviour explains basic dynamics of walking and running. Proc. Royal Society B: Biol. Sci. 273, 2861–2867.

Ghez, C., Vicario, D., 1978. The control of rapid limb movement in the cat. I. Response latency. Exp. Brain Res. 33, 173–189.

Holmberg, A., Pelletier, R., 2009. Automated blood sampling and the 3Rs. NC3Rs #16, April 2009. http://www.nc3rs.org.uk/downloaddoc.asp?id=893&page=1119&skin=0

Hudson, H.M., Griffin, D.M., Belhaj-Saïf, A., Lee, S.P., Cheney, P.D., 2010. Methods for chronic recording of EMG activity from large numbers of hindlimb muscles in awake rhesus macaques. J. Neurosci. Methods 189, 153–161.

Lauder, G.V., Anderson, E.J., Tangorra, J., Madden, P.G.A., 2007. Fish biorobotics: kinematics and hydrodynamics of self-propulsion. J. Exp. Biol. 210, 2767–2780.

Lehmann, F.O., Nasir, N., Gorb, S., 2010. Elastic deformation and energy storage of flapping fly wings. J. Exp. Biol. 214, 2949–2961.

Long, J.H., 2007. Biomimetic robotics: building autonomous, physical models to test biological hypotheses. J. Mech. Eng. Sci. 221, 1193–1200.

Long, J.H., Schumacher, J., Livingston, N., Kemp, M., 2006. Four flippers or two? Tetrapodal swimming with an aquatic robot. Bioinsp. Biomim. 1, 20.

Maus, H.-M., Lipfert, S.W., Gross, M., Rummel, J., Seyfarth, A., 2010. Upright human gait did not provide a major mechanical challenge for our ancestors. Nat. Commun. 1, 70.

Morton, D.B., 1997. The Recognition of Adverse Effects on Animals During Experiments and its Use in the Implementation of Refinement. Proc. Joint ANZCAART/NAEAC Conference on Ethical Approaches to Animal-Based Science, Auckland, New Zealand, 19–20 September.

Muscolo, G.G., Recchiuto, C.T., Hashimoto, K., Laschi, C., Dario, P., Takanishi, A., 2011. A Method for the Calculation of the Effective Center of Mass of Humanoid Robots. 11th IEEE-RAS International Conference on Humanoid Robots. October 26th-28th, 2011. Bled, Slovenia.

Muscolo, G.G., Recchiuto, C.T., Molfino, R., 2014. Dynamic balance optimization in biped robots: Physical modeling, implementation and tests using an innovative formula. Robotica. http://dx.doi.org/10.1017/S0263574714001301. available on CJO2014.

Patla, A.E., Vickers, J.N., 1997. Where and when do we look as we approach and step over an obstacle in the travel path? Neuroreport 8, 3661–3665.

Phelan, C., Tangorra, J., Lauder, G.V., Hale, M., 2010. A biorobotic model of the sunfish pectoral fin for investigations of fin sensorimotor control. Bioinsp. Biomim. 5, 035003.

Radkhah, K., Maufroy, C., Maus, M., Scholz, D., Seyfarth, A., von Stryk, O., 2011. Concept and design of the BioBiped1 robot for human-like walking and running. Int. J. Humanoid Robot 8, 439–458.

Richards, C.T., Clemente, C.J., 2012. A bio-robotic platform for integrating internal and external mechanics during muscle-powered swimming. Bioinsp. Biomim. 7, 016010.

Rusche, B., 2003. The 3Rs and animal welfare—conflict or the way forward. Altex 20 (Suppl 1), 63–76.

Russell, W.M.S., Burch, R.L., 1959. The Principles of Humane Experimental Technique. Methuen Publishing, London, UK.

Schiehlen, W., 1997. Multibody system dynamics: roots and perspectives. Multibody Syst. Dyn. 1, 149–188.

Sebelius, F., Eriksson, L., Balkenius, C., Laurell, T., 2006. Myoelectric control of a computer animated hand: a new concept based on the combined use of a tree-structured artificial neural network and a data glove. J. Med. Eng. Technol. 30, 2–10.

Seok, S., Wang, A., Chuah, M.Y., Otten, D., Lang, J., Kim, S., 2013. Design principles for highly efficient quadrupeds and implementation on the MIT Cheetah robot. IEEE Intl. Conf. on Robotics and Automation (ICRA), May 6–10, Karlsruhe, 3307-3312.

Seyfarth, A., Geyer, H., 2002. Natural control of spring-like running—optimized self-stabilization. Proc. 5th International Conference on Climbing and Walking Robots. Prof. Engineer. Publish. Lim., 81-85.
Shepherd, S.V., Platt, M.L., 2006. Noninvasive telemetric gaze tracking in freely moving socially housed prosimian primates. Methods 38, 185–194.
Sprövitz, A., Tuleu, A., Vespignani, M., Ajallooeian, M., Badri, E., Ijspeert, A.J., 2013. Towards dynamic trot gait locomotion: design, control, and experiments with Cheetah-cub, a compliant quadruped robot. Int. J. Robot. Res. 32, 932–950.
United States Department of Agriculture, Annual Report of Animal Usage by Fiscal Year 2010. http://www.aavs.org/atf/cf/%7B8989c292-ef46-4eec-94d8 43eaa9d98b7b%7D/2010_ANIMALS_USED_IN_RESEARCH.PDF
Vanderborght, B., Albu-Schaeffer, A., Bicchi, A., Burdet, E., Caldwell, D.G., Carloni, R., Catalano, M., Eiberger, O., Friedl, W., Ganesh, G., Garabini, M., Grebenstein, M., Grioli, G., Haddadin, S., Hoppner, H., Jafari, A., Laffranchi, M., Lefeber, D., Petit, F., Stramigioli, S., Tsagarakis, N., Van Damme, M., Van Ham, R., Visser, L.C., Wolf, S., 2013. Variable impedance actuators: a review. Robot. Auton. Syst. 61, 1601–1614.
Vukobratović, M., Borovac, B., 2004. Zero-moment point—thirty five years of its life. Int. J. Hum. Robot. 1, 157–173.
Webb, B., 2001. Can robots make good models of biological behavior? Behav. Brain Res. 24, 1033–1050.
Williams, F.J., Mills, D.S., Guo, K., 2011. Development of a head-mounted, eye-tracking system for dogs. J. Neurosci. Methods 194, 259–265.