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THE MECHANICS OF CARPAL VIBRISSAE OF *RATTUS NORVEGICUS* DURING SUBSTRATE CONTACT

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Abstract. Sinus hairs are tactile hairs of mammals, commonly also known as vibrissae or whiskers. The term “whisker” contemplates to the mystacial sinus hairs (mSH) in specific, which are situated around the snout of the animal. These mystacial sinus hairs can be moved actively to support and control sensing [1, 29]. The cyclic motion (whisking) of the mystacial sinus hairs was eponymous.

In many species not only mSH can be found. Studies have demonstrated a variety of sinus hairs at multiple locations on the body surfaces of mammals [13, 27]. This contribution deals with carpal sinus hairs (cSH) at the forelimbs of rats. Although known for over 120 years – cSH first were discovered in some lemurs at the end of the 19th century [2, 5] – the knowledge of structure and function of cSH in mammals is very sparse in comparison to mSH.

Carpal sinus hairs gain increasing interest since there is evidence on influences on the kinematics of the segmental chains of legs. One hypothesis is that cSH signals serve to adjust the stiffness of legs and to prepare them for the contact with different substrates or irregularities in the substrate – a function interesting for robotic locomotion.

Studies on the locomotion of animals allow examining the influence of tactile information on walking parameters when mystacial and/or carpal sinus hairs are absent. Due to their small size it is very difficult to visualize the mechanical behavior of cSH during natural movement of a living rat with conventional methods. Therefore, we are proposing the use of a so called *pedipulator* – a mechanical gearing device which guides a dissected forelimb of a rat artificially on a natural trajectory. This approach shall help to understand the functionality of cSH and to interpret results from previous motions studies with living rats.

Index Terms – sinus hair · vibrissae · carpal · locomotion · mechanics · pedipulation · touch

1. INTRODUCTION

Vibrissae (singular *vibrissa*) is the Latin term for rhythmic moving sinus hairs (as well as for the hairs in the nostrils). It is a special category of hair within the sinus hairs which are named after the follicle-sinus-complex [25]. Sinus hairs are a prominent and well known structure among *Theria* [9, 15, 17, 21, 22] which might have occurred 160 million years ago with the divergence of *Placentalia* and *Marsupialia* [16].
Sinus hairs are very specialized and categorized according to their position on the body [13, 27]. The best known and deeply investigated representatives among sinus hairs are the mystacial, also known as mystacial vibrissae or whiskers.

Carpal Sinus Hairs – Characteristics

Carpal sinus hairs are very prominent in arboreal mammals as well as in mammals with high grasping abilities [2, 3, 17]. In rats, they appear in a number of about three at the distal end of the lower arm (Fig. 1). They possess a follicle-sinus-complex with a cavernous and a ring sinus together with a high innervation and different types of mechanoreceptors like mystacial sinus hairs [8, 10]. FUNDIN et al. [8] have described several differences in type and number of mechanoreceptors between mystacial and carpal sinus hairs, which may imply different sensory function. Also differences in the attached musculature can be observed. According to our knowledge so far, carpal sinus hairs cannot be actively moved or controlled in their position like mystacial sinus hairs [1, 29].

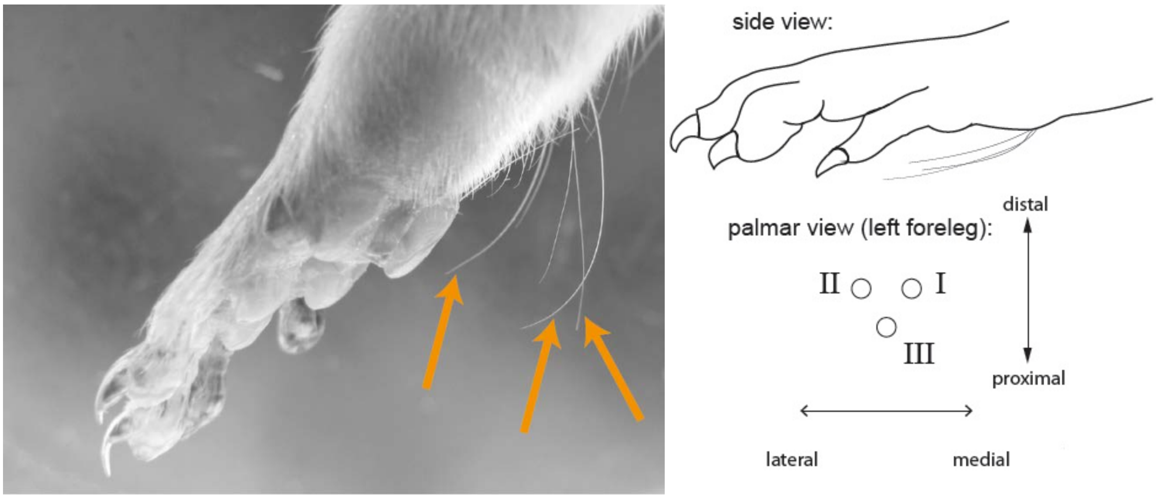

Fig. 1: Triple of carpal vibrissae (arrows) at a forelimb of *Rattus norvegicus*
right – schematic illustration with positional relations and numbering

Carpal Sinus Hairs – Biological Role

Rats inhabit different habitats which require a broad repertoire of locomotory and non-locomotory abilities. They own high grasping skills and are competent climbers which implies that tactile sensors on the forelimbs may be important for such a broad repertoire of daily activities and may assist the active sense of touch by mystacial vibrissae. Beside the tactile receptors on the palmar surface, which sense object properties at immediate contact during non-locomotory activities, tactile hairs which sense substrate properties before contact play an important role for locomotion, especially at higher speed. They might detect substrate discontinuities right before touchdown of the forelimb. Detecting irregularities is a function which implies different biological roles. These could be a measurement of the intensity of substrate disturbances, the measurement of the forelimb position relative to the discontinuity and the head, measurement of the forelimb velocity or measurement of the contact time between the forepaw and the substrate. Current evidence indicates that carpal sinus hair sense temporal parameters of the forelimb contact phase, and thereby serve as a link between the oscillation of the limbs and the oscillation of the mystacial vibrissae for speed-dependent adjustments of motion [20].

Carpal Sinus Hairs - Visualization

To understand carpal sinus hairs as a sensory system proper knowledge of their behavior is crucial, especially during their contact with the substrate. Due to the small size of cSH it is difficult to visualize their mechanical bearing under locomotion suitable for further image processing. To realize this task a different approach has to be made. Therefore we are suggesting the use of a pedipulator [11].

By investigating the relationship between form and function on carpal sinus hairs we hope to find new insights for passive – not actively moved – sensor systems in robot locomotion or other tactile tasks (in contrast to e.g. [14, 23, 26]). Analyzing the exact behavior of carpal sinus hairs in contact with different substrates during locomotion might show if they can be used as sensor for substrate roughness, vibrations transmitted through the substrate or for measuring stance phase duration, an important parameter for locomotion patterns.

2. MATERIALS AND METHODS

Motion studies

Female Lewis Albino rats (240-256 g) were used for investigating the role of both carpal and mystacial sinus hairs in the control of forelimb position during locomotion. Experiments were done with intact sinus hairs and without mystacial and/or carpal ones. A treadmill (Tetra GmbH, Ilmenau) with continuous/discontinuous substrate was used as walking set-up, surrounded by a transparent polycarbonate enclosure. The discontinuous substrate consisted of irregular located holes. Speed was controlled in the range of the preferred walking velocity of rats (0,2 to 0,5 m/s). The animals were kept in accordance with German animal welfare regulations, and all experiments were registered with the Thuringian Committee for Animal Research (J-SHK-2684-05-04/12-1).

Biplanar x-ray (Neurostar®, Siemens AG, Erlangen) was used for tracking limb, head, forelimb and trunk movements, high-speed videography for tracking mystacial whisker movement (SpeedCam® Visario G2 Weinberger-Vision GmbH, Erlangen). The acquired video data was used for different approaches. To analyze the influence of mystacial and carpal sinus hair on locomotion and to quantify rat forelimb movement for studies with the pedipulator.

The movement of the mystacial vibrissae as well as the spatiotemporal parameters of forelimb excursion were quantified frame-by-frame with SimiMotion® 3D (Simi Reality Motion Systems GmbH, Unterschleissheim). The mystacial whisker movement was quantified for detecting the scanning area and to measure deviations in the whisking behavior after removal of the carpal sinus hairs. Frequency, range of motion, spread and the shifting of the whisking field were quantified. Stride frequency, protraction angle of the forelimbs and the failure rate (relative number of steps in the holes) were measured. Statistical analysis refers to linear regression analysis, F-values, coefficient of determination. The significance threshold was set on $\alpha = 0,05$.

To obtain the necessary data for constructing the pedipulator the x-ray recordings in lateral perspective were used. The motion of the forelimb was analyzed by a video-based fixed-frame measurement using free analyzing tools (Kinova and Skillspector). Fixed points like joints were identified manually as anatomical landmarks and marked in the x-ray fixed frame.

A total of six anatomical landmarks (spina scapulae, shoulder joint, elbow joint, wrist join, knuckle and fingertip), three joint-angles (shoulder joint, elbow joint, wrist joint) and protraction angle were used to characterize the movement of the forelimb (Fig. 2). After these elements were marked manually they were analyzed by the software and transformed in a preassigned coordinate system. To minimize errors in connection with digitalization the whole data set was compiled three to five times in every gait. The arithmetic mean was used for further kinematic examinations.

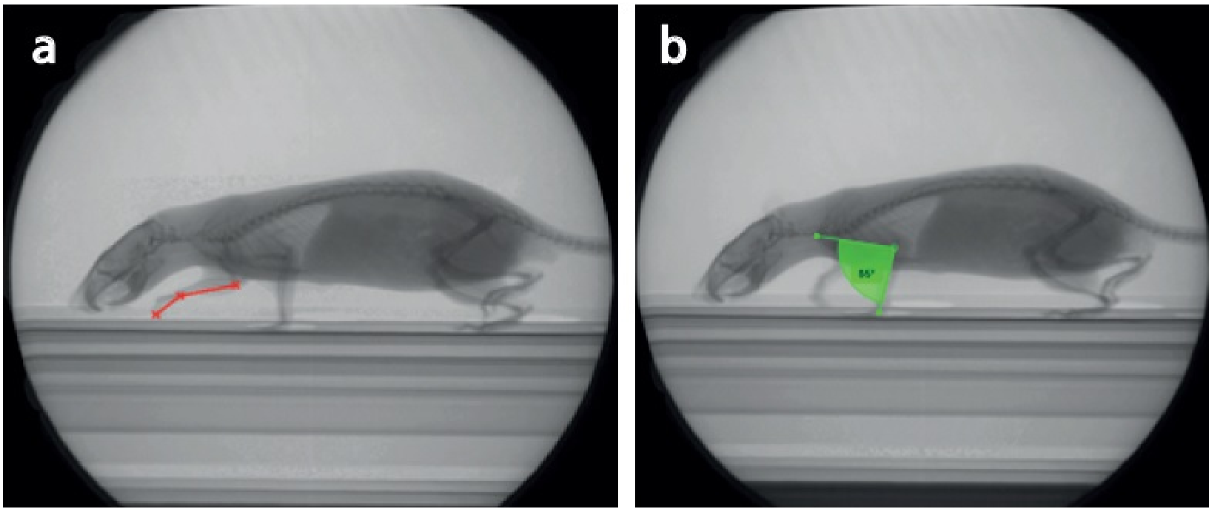

Fig. 2: Motion analysis of the forelimb of a rat during locomotion on a treadmill setup
a – marked anatomical landmarks using SkillSpector
b – marked joint-angle (elbow) using Kinovea

Carpal Sinus Hairs - Visualization

It was not possible to visualize carpal sinus hairs and their mechanical bearing directly with our setup under locomotion suitable for further image processing and quantification of their behavior. Hence we are following a different approach.

To visualize the behavior of cSH during a step cycle, we are introducing the use of a "pedipulator" – a gearing mechanism which guides a dissected leg of a rat cadaver artificially (Fig. 3) [11]. In contrast to a manipulator, which is strongly connected with industrial handling and robotics, we don't want to build a cybernetic mechanism used to perform some of the human upper limb functions [19].

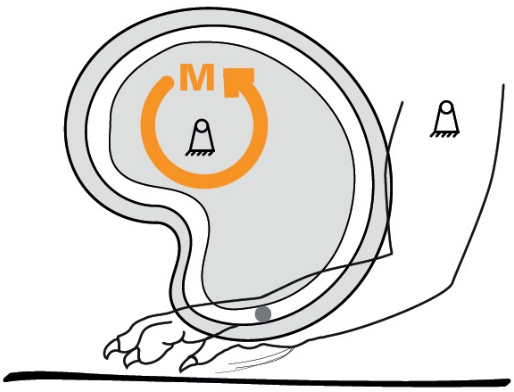

Fig. 3: Schematic illustration of a pedipulator – a dissected forelimb of a rat is guided artificially on a natural trajectory

While following the observed kinematics from cineradiography the pedipulator enables us to imitate the natural movement of the forelimb of the rat on an extended time scale. Furthermore, the pedipulator allows focusing our gaze on the exact spot of contact between the cSH and substrate, without being subject to restrictions arising with the depth of focus and uncertain contact points during natural movement of the living rat.

3. RESULTS

Motion of the forelimb

249 forelimb stride cycle between 0.24 m/s to 0.52 m/s were examined. The rats used a moderate walking gait with lateral sequence. Forelimb position, protraction angle, limb and whisking frequency as well as whisker motion were linked to animal velocity. Whisking frequency is much higher than limb frequency, both in the presence and in the absence of carpal sinus hairs.

Placement of the forelimbs was right beneath the anterior margin of the orbita where the excursion range of mystacial vibrissae have their posterior limit. In the absence of carpal sinus hairs the variation of forelimb placement increased, but the mean limb protraction angle did not change. Also speed-independent is the internal kinematics of limb elements, which we used for pedipulation. Complete results can be found in [20].

Pedipulation

First experiments observed with a high-speed microscope (Keyence VW-9000) (Fig. 4 right) indicate a contact phase of the carpal vibrissae with the substrate longer than expected. Additionally, cSH show a planar contact (Fig. 4 left) with the substrate in contrast to most simulations made so far regarding mSH (e.g. [4, 12, 28]). Associated with the planar contact, a high influence of friction between sinus hair and substrate on the forces and torques routed to the mechanical receptors in the sensor complexes of the sinus hair has to be expected. By analyzing the deformation of cSH during the whole contact phase, regarding different substrates with different friction coefficients, we hope to gain a better understanding of those specific sensory organs, which can be biomimetically transferred for the application in technical developments.

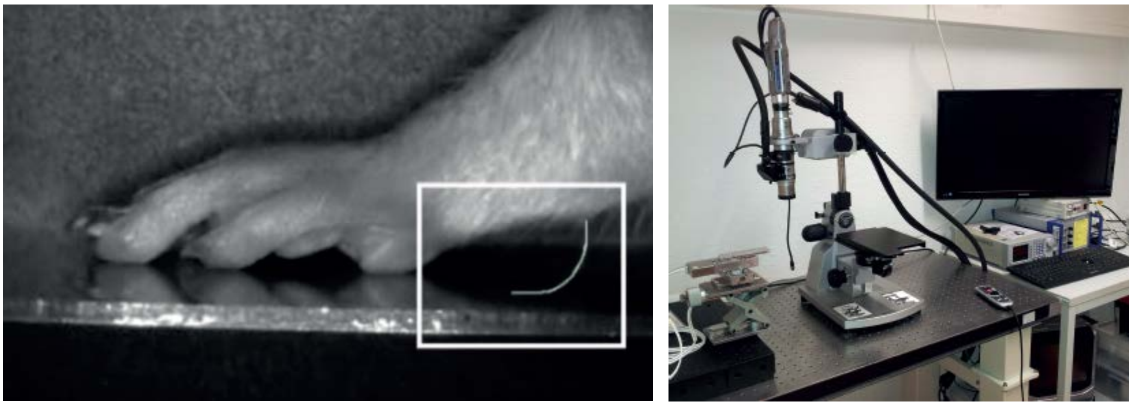

Fig. 4: left – Contact between a carpal sinus hair and the substrate during provoked movement of the left forelimb of a rat cadaver. Manually enhanced curve: carpal sinus hair, rectangle: contact area [11]
right – Workstation with digital high-frequency microscope VW-9000 (Keyence)

4. DISCUSSION

During locomotion, rats like small mammals in general, are confronted with numerous disturbances which notoriously compromise body stability. To better anticipate substrate properties before touchdown of the weight bearing forelimb, a sensor on the limbs is useful which detect irregularities. These sensors have to work during the swing phase to detect discontinuities on the place where the limbs are going to be placed next.

Previous studies documented an invariant placement of the forelimbs beneath the eye correlated to a stable protraction angle [6, 7, 24]. Without carpal sinus hairs the mean protraction angle keeps still unchanged while its variation increased. This observation implies that carpal sinus hairs influence the position control of the forelimb in a rather subtle way. The presence or absence of carpal sinus hairs had no effect on the failure rate of the limbs during walking on the perforated treadmill. Interestingly, the motion of mystacial whiskers is also affected by the presence or absence of carpal sinus hairs and might compensate the loss of this substrate sensor.

Both sensory systems seem to have a different dependence on animal velocity. Changes of animals speed lead to changes of the range excursion of the mystacial vibrissae, but only in the presence of carpal sinus hairs. If they are absent, the speed-dependent adjustment of the range of motion of mystacial vibrissae appears to be disturbed. We interpret this observation as evidence for the role of the carpal vibrissae to provide the somatosensory system with information about the animal's speed (by sensing the duration of the contact phase of the limb).

Artificial guidance of a dissected forelimb

Locomotion studies with living rats help gaining knowledge about the influence of carpal sinus hairs on general locomotion parameters and changes in the control of mystacial sinus hairs. The pedipulator can help to identify other sensory capabilities and functionalities of carpal sinus hairs while evaluating the duration of substrate contact and interactions between substrate and carpal sinus hair. Restrictions regarding that approach arise considering different sources of error.

In general a two-dimensional analysis of a three dimensional movement requires a high knowledge of errors caused by perspective and projection through the restrictions in one plain [30]. In this study these errors are negligible while the rat is moving approximately in the observed plain and is moving her limbs parasagittal. Movements out of the plain are constricted through the shiftable enclosure made of transparent polycarbonate (compare materials and methods) [30]. With the help of the assignment of different pictures of two-dimensional trajectories a three-dimensional might be possible [18] and would be part of following studies.

Depending on the realized coupling between the pedipulator and the dissected leg different methodological errors have to be taken in account. Considering the x-ray-motion study a fixation at the skeletal system – especially in the joints reviewed – might avoid errors caused by soft tissue effects (Fig. 5). Still unspecific influences will appear because of the dissection of the forelimb and the dead material. The lack of blood circulation, muscle activity and tendon stiffness will cause changes in the fixation of the carpal sinus hairs in the epidermis.

Higher variations in the angle of approach between the carpal sinus hair and the epidermis and changed Eigen-frequencies have to be expected even in fresh dissected material.

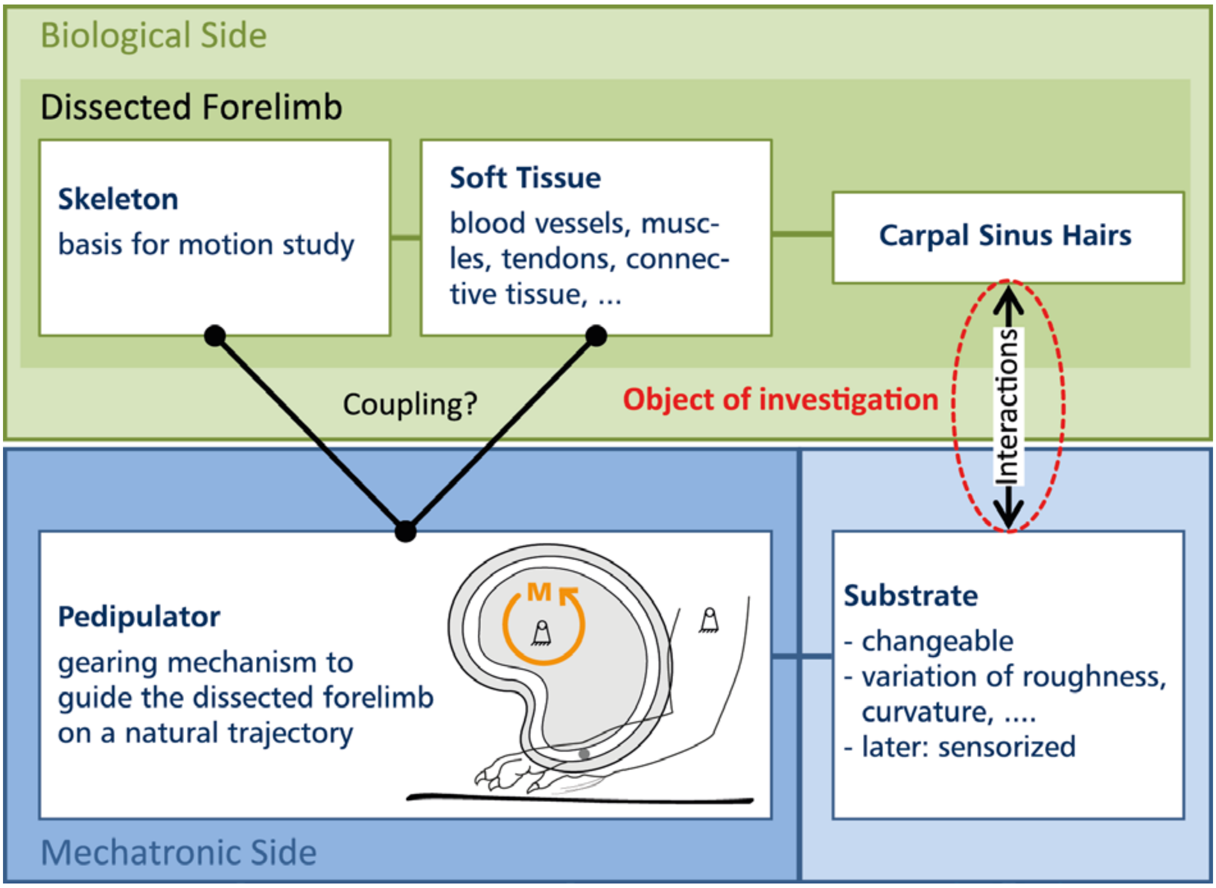

Fig. 5: Block diagram of the pedipulator in connection with different types of substrate and dissected forelimb

With regard to these restrictions the pedipulator might help to gain new insights on carpal sinus hairs. Following studies shall investigate the influence of substrate curvature and roughness. Furthermore a BASALT MUST from *Tetra GmbH Ilmenau* could be used to measure contact forces of carpal sinus hairs on side of the substrate.

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