Modeling of controllable support stiffness bio-inspired by tactile sensor systems

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Summary. Mammals exhibit sinus hairs for tactile sensing where every sinus hair is supported by its own so-called follicle-sinus-complex. This support consists of two blood sinus which seem to have an important function. Biological hypotheses suggest that, using these sinus, this support is able to change its stiffness depending on the current application of the sinus hair. Because of the size, experiments at the living object are not possible so far. Hence, we present a mechanical model as well as a demonstrator inspired by the functional principle of the biological support follicle-sinus-complex to investigate the advantages of a controllable support stiffness from a mechanical point of view.

Introduction

Sinus hairs (see Fig. 1(left)) of mammals form a tactile sensory organ with exceptional abilities. Depending on the localization of these tactile hairs on the body, they are used for different tasks, e.g. object recognition, object distinction by texture discrimination, social behavior [1], [2]. Although in focus of science, since a long time the capability and adaptivity of this sensory organ is not completely understood.
Each sinus hairs is embedded in and supported by its own own follicle-sinus-complex (FSC), see Fig. 1(right). The FSC

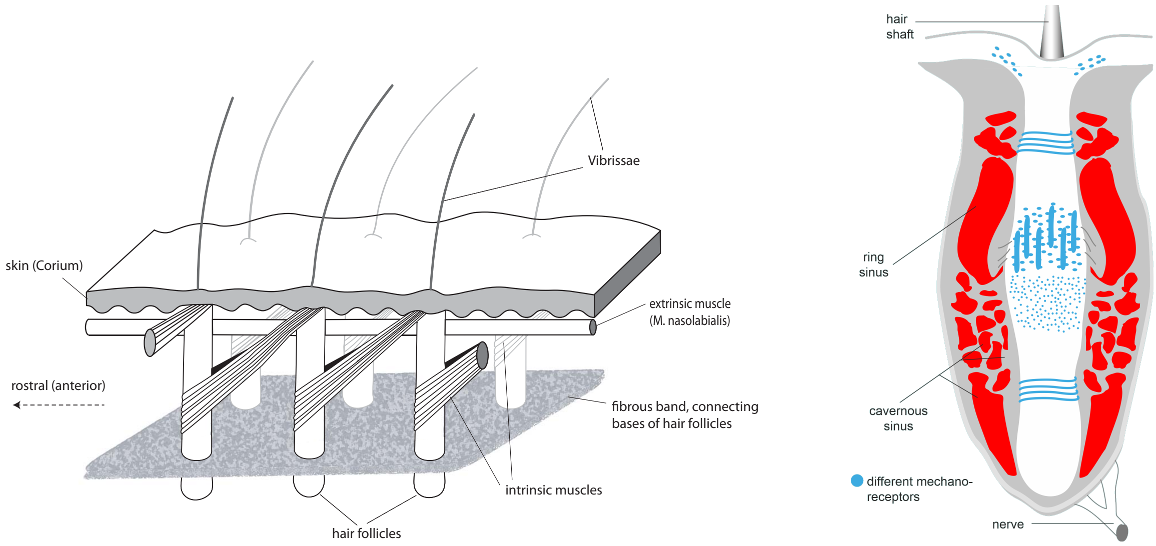

Figure 1: Left: Schematic drawing of neighboring follicles [3]; right: FSC of a sinus hair with receptors (blue).

exhibit two blood sinus (ring sinus and the cavernous sinus, see Fig. 1(right)) seeming to have an important function – hypothesis: *These sinus form a (hydraulic) bearing of the hair shaft which enables the system to change the elastic properties of this support depending on the mentioned application.*
Having a glance to the related work, different concepts are introduced in the context of changing the support stiffness of a system, especially in the context of human-friendly and service robotics. These concepts involve

- classic elements of construction and design theory (e.g. Jack-Spring-Actuator, Twisted-String-Actuator, Various-Stiffness-Actuator [4]) or
- material effects (e.g. magneto-rhelogical [5] or electro-rheological fluids).

Materials and methods

Because of the size, experiments at the living object to clarify the biological role of the sinus are not possible so far. Hence, we present a mechanical model as well as a demonstrator inspired by the functional principle of the biological support FSC to investigate the advantages of a controllable support stiffness from a mechanical point of view.
The experimental setup in Fig. 2 is based on a Various-Stiffness-Actuator [4]. The original concept is modified in order to reduce the modeling complexity, to use simple control structures (e.g. single motor control), and to achieve a high modularity.

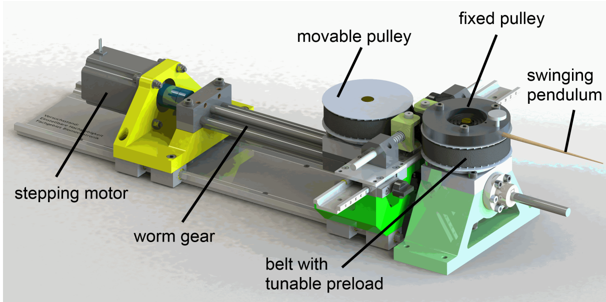

Figure 2: Experimental setup for a support of a oscillating rod with controllable stiffness.

To test various control algorithms, we set up a mechanical model of a single sinus hair (rigid-body) with visco-elastic support, see Fig. 3. For this, the pivot is connected to a natural damping and stiffness. Moreover, an additional visco-elasticity models the skin. The system is under the influence of an external disturbance force and a control torque.

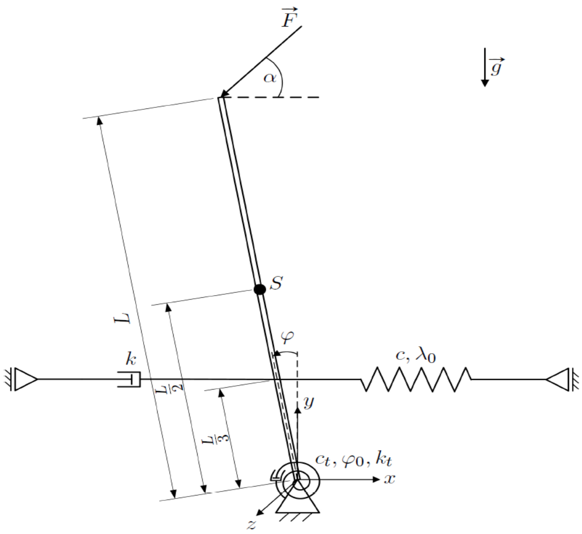

Figure 3: Mechanical model.

Applying the principle of angular momentum yields:

$$\begin{aligned}\frac{m\,L^2}{3}\ddot{\varphi} = {} & L\,F\big(\cos(\alpha)\cos(\varphi)+\sin(\alpha)\sin(\varphi)\big)\\ & + \frac{m\,L\,g}{2}\sin(\varphi) - \frac{c\,L^2}{9}\sin(\varphi)\cos(\varphi)\\ & - \frac{k\,L^2}{9}\dot{\varphi}\cos^2(\varphi) - c_t\,\varphi - k_t\,\dot{\varphi} + M_u(t)\,, \quad (1)\end{aligned}$$

with spring rates c, c_t, damping factors k, k_t, rod length L, rod mass m, gravity constant g, control torque $M_u(t)$ and disturbance force F under angle of attack α.
The goal is to adaptively control/track a chosen system's motion pattern/oscillation (depending on the application) measured in the angular position, despite the permanent disturbance force $\vec{F}(t)$ which is assumed to be unknown. Hence, we compensate the disturbance force via adjusting the stiffness using $M_u(t)$ as proposed in [3]: Using the error $e(t) := \varphi(t) - \varphi_{ref}(t)$ and defining the PD-feedback strategy $M_u(t) = -k(t)\,e(t) - \kappa\,k(t)\,\dot{e}(t)$ with a time varying gain parameter determined using:

$$\dot{k}(t) = \max\{0, \|e(t)\|\}^2.$$

Applying the control torque to the system results in a time-varying torsinal stiffness $c_t(t) = c_t + k(t)$.
In the first place, further complexities like higher degree of freedom of the pendulum and/or the support are neglected. But, model and setup allow to compare different theoretical approaches and practical realizations.

Conclusions

Mechanical supports like bearings with a controllable stiffness (based on classic elements) are able to change the stiffness over a wide range of values in different scales (micro -> meso -> macro), but lack the speed to make noticeable changes on free oscillations with medium to high damping (aperiodic case). Complementing the work in [5], present focus is on an elastic follicle-sinus complex, represented by a magneto-sensitive elastomer (MSE). The stiffness of the MSE is controlled by the intensity of a applied magnetic field.

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