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Pinocchio, a biomimetic mechatronic testbed for producing *in vitro* articulated speech

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Introduction.

Speech production results from a fine neuro-controlled coordination between breathing, phonatory and articulatory movements. In physical terms, these movements induce fluid-structure-acoustic interactions within the vocal tract. In the framework of source-filter theory (Fant 1960), the aerodynamic phase of speech is often overlooked, yet being of much importance for voiced and unvoiced speech sound production (Catford 1977). In the case of voiced speech sound, it is taken into account by myoelastic-aerodynamic theory of phonation (Jan G. Švec et al. 2021), in which glottal constriction and vocal folds vibration generate aeroacoustic sources. Our aim is to advance our understanding of speech sound production by developing a biomimetic *in vitro* testbed. Over the last thirty years, vocal-fold testbeds have evolved in complexity and biomimicry. However, most testbeds explore the physics of phonation on geometrically-fixed replicas capable of self-sustained oscillations in fluid-structure interaction, but unable to produce intonative variations. Most of the time, the testbeds are not coupled to vocal tract, and whenever they are, the resonant cavities are static 3D-printed tracts. Reproducing *in vitro* the dynamic movement of speech articulators, such as jaw, tongue, velum and larynx, together with phonation, remains a challenge. We present here the first steps in the design of a biomimetic mechatronic testbed that would integrate all phonatory and articulatory aspects important for voice and speech production.

Methods.

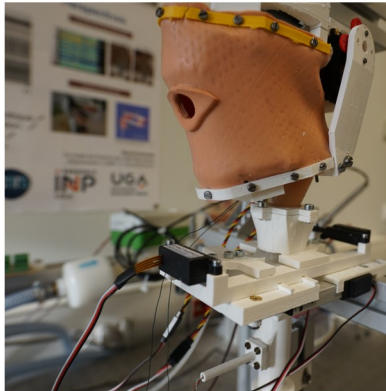
Design efforts focused on three aspects : how to breath, how to phonate, how to articulate.

The first aspect to take into account is the ability to control air supply through flow and pressure parameters. The system controls a valve opening, which is linearly related to airflow rate at the device inlet. Subglottal pressure can also be programmed using a servo loop. To stabilise the upstream jet, a settling chamber is used. A long tube leading from the chamber to the testbed avoids acoustic coupling with the subglottal tract (Lehoux, Hampala, and Jan G Švec 2021).

Choice was made to design a flexible laryngeal envelope combined with a 1:1 scale vocal-folds replica, so as to allow articulatory movements within the larynx and vocal fold stretching. In a first approach, the folds were designed to be inserted interchangeably while maintaining a seal, with the aim of gradually improving their biomimetic characteristics (Luizard et al. 2023). In a second approach, the folds were moulded together with the laryngeal envelope. Several aspects were taken into account and tailored : folds geometry, material tensile stiffness, folds anisotropy. Folds geometry was derived from common M5 models (Murray and Thomson 2012; Luizard et al. 2023). All tested folds were made of either commonly-used silicone elastomers (Ecoflex™series with increasing degrees of shore hardness) or gelatin-based hydrogels. Body and cover were homogenous (moulded together) or heterogenous (moulded apart with different stiffness, and without or with addition of a fibrous structure). The self-oscillation capabilities of each laryngeal replica were assessed.

First implemented articulatory movements were within the larynx itself, in the framework of Laryngeal Articulator Model (Esling et al. 2019). The vocal folds can be adducted or abducted, imitating the phases of breathing and phonation. They can be stretched and compressed into the anterior-posterior direction, and compressed or uncompressed into the medial-lateral one. Secondly, a geometrically-realistic and articulatory-driven vocal tract was designed, inspired from Arai's vocal-tract models (Arai 2016). A FE model of the tongue was used to design the tongue mould (Hermant, Perrier, and Payan 2017). Two primary articulatory movements were implemented : mandibular motion and shaping of the oral cavity with the movement of tongue body and apex.

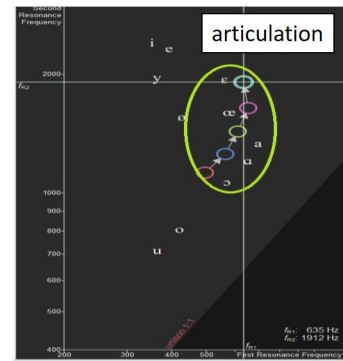
A. Pinocchio vocal-tract, jaw and cheeks



Tongue



C. Behavior assessment



B. Pinocchio larynx



vocal folds

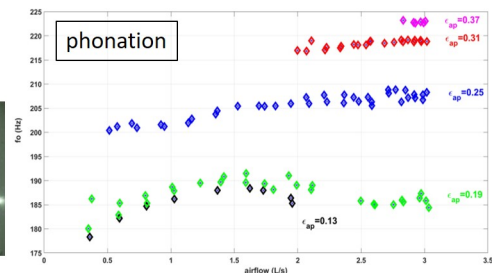
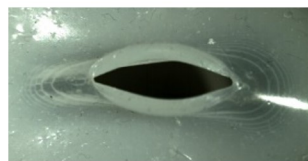


Figure 1: Presentation of the pinocchio testbed.

Results and discussion.

Figure 1 presents the complete system, called *pinocchio*, and its phonatory and articulatory capabilities.

Phonation The vocal-folds replica were able to self-oscillate with and without a vocal-tract, over a wide range of flow rates and for different degrees of tensile stretch. First main factor of variability in vibratory behaviour was the folds geometry. While long (20mm at rest) and thick (4mm) folds did not allow a self-oscillation frequency in the expected range of human speech (Luizard et al. 2023), shortening the length at rest (down to maximum 12mm) and slimming the fold (down to 1.5mm) achieved the goal of a self-oscillation frequency up to the range of female speech (f_o from 180 to 220 Hz) as shown in Figure 1C. The latest version of the vocal-fold replica allowed for increasing f_o with increasing pre-strain in the anterior-posterior direction (ϵ_{ap}).

Articulation We explored the vocalic space produced by movements of jaw, tongue body and apex movements (see Figure 1C top panel). F1 varied moderately between 500 and 700 Hz, mainly in relation to mouth opening induced by jaw movement. F2 varied between 1000 and 2000 Hz with tongue and jaw movements. At this early stage of his life, Pinocchio was able to produce vowels in the surrounding of [a].

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