Pneumatibles – Exploring Soft Robotic Actuators for the Design of User Interfaces with Pneumotactile Feedback

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ABSTRACT
This work explores an emerging category of interfaces: ***pneumatibles*** – interactive, pneumatically driven actuator/sensor elements, made from pliable materials and inspired by soft-robotics principles – and their potential for the design of tangible interfaces with integrated *pneumotactile feedback*. We present a novel pneumatic control-system, specifically designed for pneumotactile applications and a case study of a pneumatically actuated, pressure sensitive button *pneumatible* capable of providing tactile feedback. Our work further contributes to a better understanding of the underlying *technical parameters* (i.e. air-pressure, material properties, dimensions, actuation-sequences, etc.) that determine the design space of soft and pliable actuators for providing distinct tactile stimuli and enabling expressive control. We provide insights learned from the process of constructing and controlling pneumotactile actuators and present a preliminary user study, focused on participants' ability to identify pneumotactile feedback patterns. Finally, implications for the design of pneumotactile interfaces and the transfer of principles from soft-robotics to HCI are discussed.

Author Keywords
Tangible Interaction, TUI, Soft Robotics, Pneumatics, Tactile Patterns, Materials, Pneumatibles, Pneumotactile Feedback, Haptics, Fabrication.

ACM Classification Keywords
H.5.2.: User Interfaces: *Haptic I/O; Prototyping*

INTRODUCTION

The interface between humans and interactive technology has long been characterized by a rift between the soft touch of the human body and the rigid components of the machine. This gap should be questioned when designing tangible user interfaces. A rising interest in the role of materiality [3] for tangible user interfaces (TUIs) further motivates the exploration of different materials, their look and feel and their behavior. Actuators, sensors and structures made from soft, pliable materials such as silicone rubber provide an alternative to rigid interface elements and open up a space for the design of novel user interfaces. The physical characteristics of soft materials can be leveraged to achieve seamless, dynamic shape change without the need for complex mechanisms, and actuators can even be fabricated from cohesive mono-materials. This also appears beneficial for applications close to, or even *on* the user's body, providing viable alternatives for assistive devices, ergonomic adaption, medical applications or wearables.

Recent research [27] suggests the use of soft, pneumatically driven actuators in HCI, inspired by soft-robotic principles [10]. The transfer of methods from this area of robotics to tangible interaction design deserves further exploration, but work in this area is still in its infancy. To utilize the potential benefits of soft mechanisms and sensors, more investigation is needed. Our work begins to explore and define the basic parameters (as well as limitations) of this technology and contributes to the technological foundations for generating recognizable and meaningful tactile feedback through pneumatically actuated soft-robotic interfaces, made from silicone, with integrated sensing capabilities.

In the following, we give a brief overview of current research on shape-change and the application of soft-robotic principles in HCI. We then present our development case study of a pneumatically driven, soft actuated button that provides *pneumotactile feedback* and enables one-dimensional *variable force input*. This serves as a simple example of an emerging *category* of interfaces that we call ***pneumatibles*** – *pneumatically actuated, pliable interface components, capable of generating dynamic tactile stimuli*.

The process of constructing and controlling such *pneumatibles* enabled us to explore the effect of various structural and control-related parameters on the actuator's tactile performance. Even with simple *pneumatibles,* the interactions between multiple parameters profoundly affect the tactile characteristics. We describe how to build soft-robotic actuators that enable both tactile feedback *and* user input, and discuss our initial experiments on tactile patterns. We present a preliminary evaluation and discuss the insights gained through this exploratory case study.

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BACKGROUND

Actuated tangibles commonly employ a combination of motors, levers, gears, and other integrated mechanical components to provide haptic guidance or tactile feedback. This can enable strong and high resolution output and is becoming more accessible for haptic applications [6]. Interfaces with actuated interactive shape-change can be categorized as dynamic *shape displays* [19]. Rasmussen et al. [20] have further categorized shape-changing interfaces. While there are various methods for achieving shape-change [2], many rely on rigid structures and materials [9]. As an alternative approach, by leveraging methods from soft-robotics we can create and animate three-dimensional physical shapes, generate motion and provide new means for user input. This further provides simultaneous visual and tactile output if the shape-change is large enough to be seen, thereby offering inherent multimodal feedback.

Depending on the material chosen, soft actuators and sensors can be made water- and even acid-proof, mechanically robust, vibration resistant, and allow for spatial separation of pliable interface components and the rigid control hardware. This renders them interesting whenever environmental conditions [26] or the contexts of use require such separation. Fluidic soft actuators further lend themselves to integration with existing systems that already contain pneumatic or hydraulic components, such as modern cars, medical equipment, exoskeletons, prosthetics, or household appliances, where they can be leveraged to enhance the user experience, create organic shape-change, or enable new applications. Moreover, soft actuators can be designed to generate *isotropic* force output, which is hard to achieve mechanically with rigid structures. When deployed in proximity to people, rigid mechanisms with high actuation forces or freedom of movement can pose a physical threat and often require additional safety measures, as in industrial robotic appliances. In contrast, pliable materials for actuation allow for inherently *mechanically compliant* [10] motion, i.e. a soft actuator physically deforms when it encounters an obstacle, making it safer for human contact or for the automated manipulation of fragile objects, without the need for additional sensors or advanced control systems.

Related Work

Common approaches for tactile feedback include electrotactile and vibrotactile [1] feedback. The former has been demonstrated to create localized tactile sensations [13] and can modulate friction on touch surfaces to render tactile 3D features [12]. Vibrotactile actuators provide a low-cost and compact solution for unobtrusive feedback, but localized stimuli are hard to achieve as vibrations can spread across the device. Both approaches have in common that they do not create visible effects, and thus require sustained physical contact with the interface hardware to be perceived.

Slyper et al. [22] demonstrated the process of building simple soft sensing elements with integrated electronics. A method for 3D printing pneumatically-driven device controls, using a combination of rigid and pliable materials, has also been explored [25]. Park et al. [15] presented a soft sensing element that can detect 3-axis deformation by measuring changes in resistance of liquid metal embedded in silicone. A similar sensor based on an optical sensing approach for shear- and pressure detection is commercially available [28] and has been demonstrated for use in robotics or interface applications. Seoktae et al. [21] introduced soft robotic methods to HCI. Harrison et al. [8] constructed an overlay for screens that contains prefabricated air-chambers which can be in- or deflated to create physical buttons that dynamically emerge from a display surface. Changes in air-pressure are measured to detect the force of button presses. A commercially available case for tablet computers [24] uses a screen overlay with embedded liquid-chambers to enable shape-change. Other approaches that combine shape-change with computer graphics have been presented [11, 4].

While prior research has mainly focused on showing the basic principles and the feasibility of creating different types of *pneumatibles*, our work makes a first attempt at *systematizing the design space* of such pneumotactile actuators for HCI applications by identifying and describing the fundamental *technical parameters* that influence the capabilities of such devices for generating tactile feedback. Furthermore, we also make the contribution of a proof-of-concept design for a novel *pneumatic control system* specifically constructed for the requirements of pneumotactile applications, which eliminates unwanted perceivable interferences between motorized air-pumps and tactile actuators.

TECHNOLOGY EXPLORATION

Soft-robotic actuators commonly contain one or more air-chambers that can be inflated using pressure sources such as motorized membrane-pumps, manual balloon-pumps, syringes [14] or similar. The flow of air in and out of the actuators is usually regulated via solenoid valves to achieve a controlled deformation of the air-chambers by modulating the internal air-pressure. The technical principles for basic shape-change by modulating internal air pressure are relatively straightforward and have been described in an HCI context [8,27]. PneuUI [27] and related work [14] demonstrate how basic shape-change can be achieved with different pliable actuators. However, for precise and responsive control of *small* shape changes, as required for fine-grained tactile feedback, a careful balance between multiple parameters of the soft-robotic actuator and the control system is required. Even in seemingly simple setups, the interactions between various parameters of the system can profoundly affect the overall tactile performance. Therefore, we purposely focused our case study of a *pneumatible* on a *simple form factor* and interaction – a *button-like* actuator containing a single air chamber – as this allows us to systematically investigate the structural design parameters (see Figure 1) that influence the behavior and tactile characteristics. The schematic provides an overview of the various factors relevant for the design of *pneumatibles*, based on the form factor chosen for our case-study.

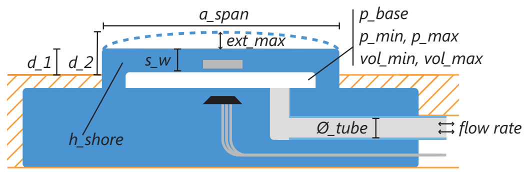

Figure 1. Schematic cross section of an exemplary *pneumatible* with indication of variable parameters. (locations of a magnet and hall-effect sensor for user input are also shown).

During initial experiments in constructing *pneumatibles,* we identified various parameters that have to be considered in the design of such actuators. Table 1 gives an overview of these parameters. For more complex actuator shapes, additional factors, such as varying wall-strengths and -rigidness that result in *anisotropic* deformation of air-chambers, might be identified and added to the list. The combined effects of these parameters in combination with the underlying control system determine the pneumotactile capabilities of an actuator.

h_shore	Hardness of the material (on the *Shore* durometer scale)
p_min	Minimum air-pressure level
p_max	Maximum air-pressure level
p_base	Baseline air-pressure (i.e. initial pressure level at rest: *no* pneumotactile feedback and *no* user input present)
vol_min	Volume of air-chamber at zero inflation
vol_min	Volume of air-chamber at maximum inflation
a_span	Surface span/area of the inflated walls of an air-chamber
ext_max	Maximum action/travel-distance
s_w	Thickness/strength(s) of air-chamber wall(s)
d_1	Extension of non-pressurized air-chamber
d_2	Extension of fully pressurized air-chamber
Ø_tube	Diameter of the tube used to pressurize an air-chamber
flow rate	Maximum flow rate to/from air-chamber enabled by the control system

Table 1. An overview of variable parameters for the design of pneumotactile actuators.

Insights from Initial Explorations

Our initial series of informal experiments in creating simple *pneumatibles* with a single air-chamber indicated that – given sufficient air pressure supply and flow rates – the overall *volume of the air-chamber* (*vol_min*, *vol_max*), *hardness* (*h_shore*, measured on the *shore durometer* scale [23]), and structural properties such as the *strength* (*s_w*) of the air-chamber walls have the largest effect on the speed of actuation and the precision of tactile stimuli. The controlled *transmission of force* to the users' fingertips is a challenge in the design of soft actuators for tactile applications. In our explorations, force transmission was profoundly influenced by the combination of material *hardness* and the *baseline air-pressure* (i.e. air-pressure *p_base* > *p_min* and *p* < *p_max*), which was modulated to create tactile stimuli via relative changes in air-pressure. The ideal baseline pressure value for generating distinguishable tactile stimuli furthermore appeared to vary in relation to structural parameters, particularly the surface *span* of the inflated air-chamber. Larger surface spans increased damping, thereby reducing the achievable tactile precision. Higher baseline pressures reduced damping and allowed for increased detail in the tactile cues. As expected, the use of softer materials also increases *damping* effects that attenuate the pneumotactile output. Smaller air-chamber volumes generally allow for faster actuation, and smaller surface spans of the actuator further reduce damping effects, but the compliant properties of soft materials appear to affect the performance of pneumotactile actuators the most. Stiffer materials (hardness > Shore A 40) cause less damping and thereby improve tactile output. However, they require disproportionally higher pressure levels for actuation or, alternatively, very thin wall strengths, which render actuators prone to leaks and failure [25]. The use of semi-, or even non-pliable materials for building actuators with a foldable [27] or expandable structure has been demonstrated to create inflatable structures and could provide a way to overcome this issue. The speed and rate at which the *pressure change* inside a pneumotactile actuator can be controlled is also critical for providing distinct tactile feedback [7,20]. This is limited by the maximum *flow rate* through valves and other parts of the pneumatic system and influenced by the available *air-pressure*. These factors and their interplay must be considered and carefully proportioned when developing pneumatically driven tactile interfaces from soft materials.

Design of Pneumatibles

Based on the insights from our exploration of fabricating and controlling *pneumatibles* of different form factors (e.g. bending actuators, inflatable grasping handles, spheres, etc.) and with differently sized air chambers, we constructed a simple pneumotactile actuator – an actuated button with *pneumotactile feedback* and *variable force input* [18]. This simple instance of a *pneumatible* serves as a case study to explore the effect of individual parameters on the tactile capabilities of such actuators and provides a base for the ongoing development of a pneumotactile control system.

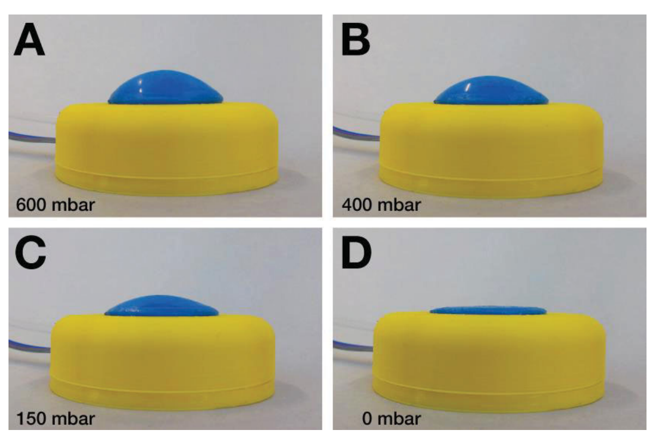

Figure 2. An exemplary case study of a simple *pneumatible* in the form factor of a *button* at different levels of inflation.

The *pneumatible* actuator (Figure 2) was molded from platinum silicone[1] (Shore A 30), which delivers a good combination of robustness (elongation at break value 339%) and actuation pressure (700 mbar for maximum safe extension). The actuator contains a single, round, *zero-volume* air-chamber [16] that contracts completely if no air pressure is applied. The air-chamber has a minimum wall strength (*s_w*) of 2.5 mm and an outside diameter of 30 mm. It can be inflated to expand upwards with a maximum travel distance (*ext_max*) of 15 mm. The cured air-chamber is molded on top of a round silicone base (50mm x 10mm) with an integrated hall-effect sensor for measuring user input. The internal volume of the fully inflated air-chamber is approximately 5 milliliters (ml). The entire silicone structure is embedded into a rigid, 3D-printed bezel to restrict the direction of extension during our study. A silicone tube connects the device to a pressure source. Figure 3 gives an overview of how the actuators were made and shows the location of the inlaid components that add sensing capabilities.

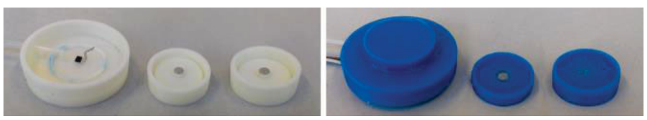

Figure 3. (left/white) 3D-printed molds: base-mold with hall-effect sensor and silicone air-tube, two air chamber wall molds with magnets. (right/blue): assembled actuator, two air-chamber walls of different strengths with integrated magnets.

A Pneumotactile Control System

An advantage of soft actuators in robotic applications is that these can be operated with fairly large tolerances in the control system. This is because *compliant,* deformable actuators mechanically compensate for control errors, such as overshoot. Basic shape-change can be attained even with relatively coarse changes in air pressure, and latencies are often tolerable. This approach is not sufficient to realize responsive pneumotactile feedback, and more precise control systems are needed, since human hands are sensitive to very small changes in frequency or texture [1,7,19]. A direct connection between a running air-pump and a *pneumatible* actuator would create noticeable oscillations in pressure.

To address these issues, we designed a control system for pneumotactile feedback (Figure 4). We use a low-cost *diaphragm air-pump* (40 L/min flow rate, 1.5 bar operating pressure) to pressurize a *storage tank* (5 liter pressure sprayer, max. 5 bar), that can alternatively be filled with an integrated manual air-pump. An additional pressure tank decouples the actuator from pressure fluctuations caused by the pump to avoid unwanted interferences. The flow of air from the storage tank to this second *supply tank* (500 ml) passes a *unidirectional valve* and can be controlled using a three-port, two-state, normally closed *solenoid valve*[2] (V1). The supply tank is connected via an additional solenoid valve (V2) to the *pneumotactile actuator*.

[1] Mold Star 30, Smooth-on Inc.

[2] SMC 070 Series

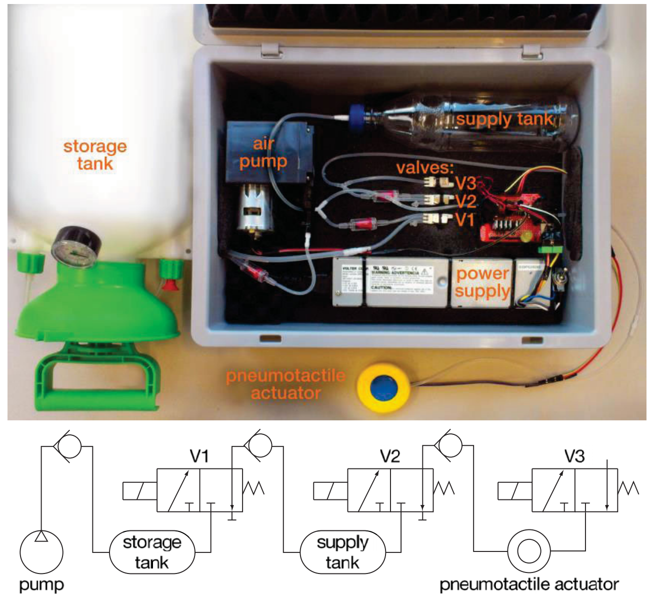

Figure 4. Pneumotactile control-system in soundproofed case and schematic of the system.

The *storage tank* is operated at a pressure level[3] of ~1400 mbar. A lower pressure level (1100 mbar) is maintained in the *supply tank*. This allows adjusting the supply tank pressure, even when the pump is not running. The pump is only enabled when the valves between storage and supply tank, or between supply tank and actuator are closed. The storage tank volume further serves to reduce pump runtime. A third solenoid valve (V3) controls deflation of the actuator. Three *pressure sensors*[4] measure pressure levels inside the actuator and the two tanks. The sensors, solenoid valves and air-pump are connected to a microcontroller (Arduino Uno R3) that implements the tactile patterns and regulates the tank pressure using a standard PID-controller algorithm as commonly used in industrial process-control.

While achievable physical response times of soft, pneumotactile actuators are limited by the switching times of valves and further affected by damping effects, caused by the actuator’s material properties, we were able to create basic, distinguishable pneumotactile patterns with this setup.

Reliably Sensing User Input

Measuring the absolute air-pressure inside an air-chamber to detect user input is suitable for some applications [8,21], but does not provide reliable sensing in combination with pneumotactile feedback. The measured internal air-pressure is a combined effect of in-system pressure and any extraneous force exerted by the user and cannot be properly differentiated from system-generated pressure changes.

To implement simple and robust input sensing, we integrated a linear hall-effect sensor[5] into the silicone base and

[3] All pressure values given in this paper are *gauge* pressure values, i.e. relative to atmospheric pressure

[4] Freescale MPX5500DP

[5] Honeywell SS495A

molded a small neodymium magnet (1.5 mm x 5 mm) into the top silicone surface of our *pneumatible*. This allows to precisely measure the depth of indentation when the button is pressed. Based on this information, we can generate relative changes in air-pressure to create tactile patterns depending on the user's absolute vertical finger position.

PRELIMINARY STUDY

We have conducted a preliminary user study that investigates the potential of *pneumatibles* as a new class of pliable tactile feedback devices. The study serves as a starting point to develop a better understanding of their current capabilities and to identify directions for further research. By testing tactile performance at different pressure levels, the study focused on developing a better understanding of the *baseline air-pressure level* (i.e. *the initial pressure level* onto which patterns are layered*)* at which such actuators should be operated for best tactile performance. *Three* different baseline air-pressure levels were chosen, based on insights gained from previous explorations and observations of the physical extension of the pressurized actuator. Deformation of the actuator at the highest baseline pressure (*p_baseA* = 600 mbar) caused the maximum safe extension of the air-chamber. At the lowest pressure level (*p_baseC* = 150 mbar), the actuator was just sufficiently inflated to provide the travel distance for generating the pneumotactile patterns used in the study. The intermediate pressure level (*p_baseB* = 400 mbar) was chosen as it caused a physical extension of the actuator that marked the centerline between the upper and the lower position.

A single silicone button with pneumotactile feedback was used for the study (Figure 2). The actuated zero-volume air-chamber had a wall-thickness (*s_w*) of 2.5mm. In our previous, informal explorations this seemed to deliver good tactile performance compared to thicker wall strengths. The button was connected to the control system described earlier. All noise-emitting components were mounted inside a soundproofed case to dampen any sound of the control system, and polyrhythmic electronic music was played from a speaker placed right in front of the participant to further mask any audible cues emitted by the actuator. After a training sequence, the actuated button was placed inside a box that served as a sight protection screen to prevent the participants from obtaining visual cues by looking at the device (see Figure 6).

Tactile Patterns

Using our control system we can modulate the pressure level inside the pneumotactile actuator at various frequencies and intensities, and thereby create different pneumotactile patterns from short bursts of pressure. The tactile sensation created by the system essentially resembles the impression of touching an oversized, mechanically dampened, long-travel tactile button with variable detents and adjustable softness. However, unlike traditional tactile switches or silicone keypads, the *pneumatible* actuator is also capable of actively exerting force through a pliable surface. The resulting feeling could be described as touching a sheet of pliable rubber or silicone that is actively deformed from below by a finger or soft mechanism. One user expressed this sensation as "feeling mechanically distinct, yet strangely organic".

Our initial explorations had indicated that simple rhythmic changes in air-pressure can be easily distinguished. However, the design space of simulating a variety of tactile sensations through *pneumatibles* still awaits more detailed explorations to identify patterns and control sequences specifically suited for pliable pneumotactile actuators. For our preliminary study, we created a series of five simple tactile detent patterns. The patterns are generated by sequential reductions of air pressure (*p*), which is repeated *one to five times*. Following this rhythmic deflation, the inverse pattern (increase of air-pressure) is generated, with the same number of steps. Figure 5 presents an overview of five pattern sequences consisting of one to five detents, similar to the patterns used in our evaluation.

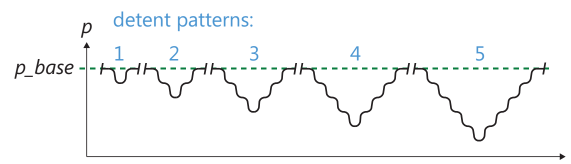

Figure 5. Schematic depiction of the tactile detent patterns used in the evaluation.

As the user presses down on the inflated actuator and reaches the activation threshold (a defined distance between magnet and hall-effect sensor) the pattern is played back. For the *descending* phase (actuator contracts downwards), the deflation time per step lasted 25ms, followed by a 75ms pause. For the *ascending* phase (actuator expands upwards), the inflation was set to 17ms per step, followed by a 75ms pause. The different time intervals are required to achieve equal relative pressure changes. The change rate is dependent on the pressure offset over the valve, which is different across the inflation- and the exhaust-valve of the actuator.

Evaluation Setup and Procedure

9 participants took part in the study (aged 21 to 39, ø 27.7 years, 3 female, 6 male). All had little to no prior experience using interfaces with tactile feedback, beyond the ubiquitous vibrotactile feedback found in mobile phones. The experimenter first explained the purpose and process of the study and the participant was asked to go through a predefined *training sequence* to familiarize herself with the behavior of the actuator. Then, the button was placed inside a box that prevented the participant from obtaining visual cues. Participants operated the actuator with the index and middle finger of their dominant hand. They were asked to press the button and identify the *number of detents* encountered in the *downward direction* after crossing the activation threshold. The first sequence of detent patterns was generated at the highest baseline pressure level (*p_baseA*) which had provided the most easily identifiable tactile feedback in a pilot test, followed by a second and third run, each at decreased pressure levels (*p_baseB*, *p_baseC*).

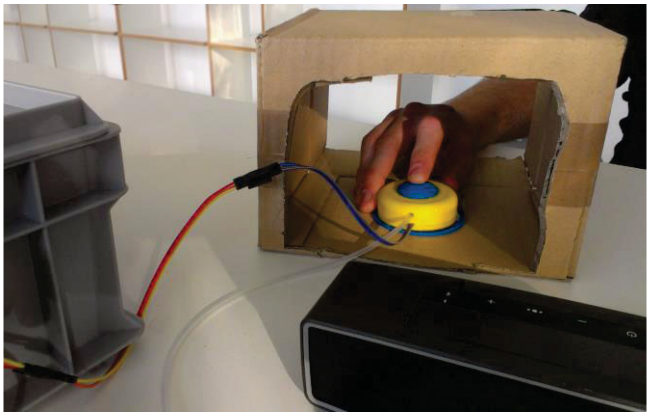

Figure 6. The evaluation setup (pneumatible, control system in soundproof case, sight protection screen, loudspeaker)

Each number of detents (one to five) was presented three times in randomized order for each of the three baseline pressure levels, yielding a total of 135 button presses per participant (45 presses for each of the three baseline pressure levels). After each sequence of pressing and releasing, the button was deflated and the experimenter noted the number of detents identified by the user (“one”, “two”, “three”, “four”, or “five”), before the button was re-pressurized and the next detent pattern was activated. The subjects were notified after completing a series of 45 trials that the baseline pressure level would be decreased for the next round. The relative pressure changes for generating the detents were fixed. After the three series were concluded, users had to rate at which pressure level they felt most *confident* and were asked for their *preference* of which pressure level they thought felt best.

Observations and Preliminary Findings

The first encounter of participants with the pneumotactile button was sometimes characterized by an emotional reaction or comment. Participants noted during the initial training phase that the pattern with one detent was “cute” and “has character”. This supports the assumption that soft actuators could be suited to convey emotions and enhance the user-experience in tactile interactions and is also backed by previous research [17].

Participants were able to correctly identify between 21 and 41 detent patterns out of all 45 trials, with an average of 29 correct guesses. Thus, about one third of guesses were wrong by either +/-1 or +/-2. The majority of participants (seven) correctly identified the number of detents between 26 and 31 times out of 45 trials (error rate: 14 to 19). All baseline pressure conditions performed roughly identical in terms of overall deviation between actual detent patterns and participants’ guesses (errors per pressure level: *p_baseA*: 50, *p_baseB*: 46, *p_baseC*: 47). It can be seen in Figure 7 that identification rates drop with patterns of more than 3 detents across conditions, and participants tend to underestimate the number of detents. However, the lower pressure conditions seemed to perform worse in terms of participants making larger errors in their guesses (Figure 8).

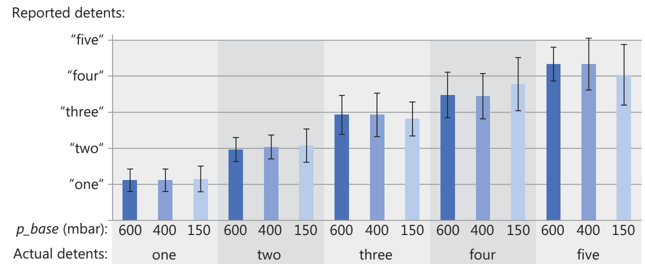

Figure 7. Reported detents per baseline pressure level:means and SD, note: the the size of individual errors is not reflected).

Guesses that were +/- 2 digits off from the actual detents were more frequent at lower baseline pressure levels. At the highest pressure level only small errors of +/- 1 occurred (number of guesses with error = 2, *p_baseA*: 0, *p_baseB*: 5, *p_baseC*: 10). This is despite the potential learning effect of each participant starting at the highest pressure level and continuing to lower base levels.

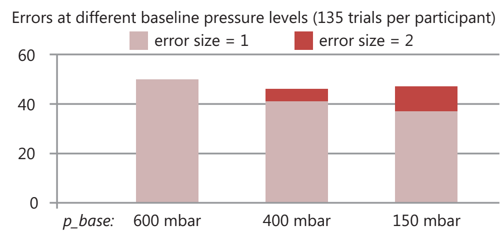

Figure 8. Error size per baseline pressure level (*p_baseA,B,C*)

The subjective opinions expressed by participants at the end of the study correlate with the measured accuracy in identifying the patterns. Participants rated the higher pressure conditions *p_baseA* and *p_baseB* as the most unambiguous that provided them with the most *confidence* in identifying number of detents (confidence per baseline pressure level: *p_baseA*: 4, *p_baseB*: 4, *p_baseC*: 1), but *generally preferred* the feeling of the medium pressure level (preferences: *p_baseA*: 0, *p_baseB*: 8, *p_baseC*: 1). Some participants stated that interacting with the highest pressure condition required a lot of effort and caused a “tense finger” position after a while, mentioning that it required a different hand posture, having to “press perpendicular” on the button with a flexed finger from the top. This was reported to strain the finger joints, whereas the lower pressure conditions could be controlled with a “relaxed”, extended finger. This was also observed by the experimenter during the study. Users also stated that a passive tactile indicator could be useful for “adjusting the finger position” to correctly “identify the ideal point” for interacting with the actuator. The lowest pressure condition (*p_baseC*) was considered too ambiguous, although some liked its “soft feel” and generally expressed affection for the “organic qualities” of soft materials.

CHALLENGES FOR SOFT-ROBOTICS IN HCI

To leverage the capabilities of soft-robotic principles for HCI applications, particularly for responsive pneumotactile feedback, a variety of challenges must be addressed. The use of soft, compliant materials inevitably introduces damping effects that limit speed and precision of tactile output. Exploring materials with adjustable stiffness [5] for pneumotactile feedback could be a direction for further research. Another challenge is the miniaturization and simplification of the required hardware. Our ongoing work investigates the use of alternative pressure sources, such as compressed CO_2 cartridges, for soft-robotic applications. They could substitute motorized-pumps and batteries and can be regarded as compact pressure generators with integrated power supply, making them suited for mobile applications.

CONCLUSION

We have presented a case study that begins to explore the implications and design space for pneumatically actuated feedback, based on the example of a pressure sensitive *pneumatible* button actuator. We have contributed a *control system for pneumotactile applications* that is designed to eliminate unwanted perceivable interference between air-pumps and actuators by decoupling the air-supply from the actuator using secondary pressure tanks and supply valves. This provides a platform for ongoing work on exploring and controlling *pneumatibles*. Additionally we contributed to a clearer understanding of the design space for pneumotactile actuators by providing a list of basic *parameters* that need to be considered when designing interfaces that leverage soft and pliable, actuated structures to provide tactile feedback. We conducted a preliminary evaluation, as an initial step to better understand how *compliant* actuators can be used to create tactile sensations. The results show that pneumotactile stimuli from pliable actuators *can* be differentiated, particularly at higher (e.g. 600 mbar) and medium (e.g. 400 mbar) *baseline pressure levels*. However, the tactile capabilities of such actuators are also strongly influenced by structural design decisions, the materials used, and the capabilities of the control system.

Our evaluation indicates that the use of pliable, compliant materials has general limitations for providing fast and precise pneumotactile feedback, due to the damping inherent to soft materials. To achieve more distinct tactile sensations, either the stiffness of the material or the internal system pressure level needs to be increased. This reduces some of the soft characteristics of the actuator, such as mechanical compliance, in exchange for better resolution of tactile feedback. Therefore, when a combination of soft materials *and* precise tactile feedback is required, one must either sacrifice some of the advantages of soft materials by using more rigid actuators, or accept compromises in the quality of achievable tactile feedback. This tradeoff raises questions for future research. Instead of attempting to re-implement mechanically inspired tactile feedback patterns (mechanical ridges, etc.), future work in this field should aim at developing pneumotactile patterns specifically designed to exploit the unique properties of soft actuators, thereby leveraging the qualities inherent to the material.

Suitable tactile patterns for compliant *pneumatibles* are more likely to be found in slow(er) shape change or organically inspired morphing, but may also include tactile indication of discrete events (as shown in our study). Concerning limitations of our preliminary study, it should be noted that the use of patterns of different duration might support participants in identifying the detent patterns from their length (i.e. 2 detents take more time than 3). Future studies (with more participants) should utilize equal length patterns.

Different types of pneumotactile actuators such as graspable or body-mounted *pneumatibles* deserve special attention and their control parameters have to be evaluated separately. Ongoing work by members of our group is focused on exploring the structural parameters and developing a greater variety of form-factors for other *pneumatible* actuators, aimed at developing a better understanding of how these affect overall tactile performance and will further evaluate a greater variety of tactile patterns. Future work also aims at implementing and evaluating sensing elements capable of detecting more expressive gestural input such as shear, pinch, pull, and similar. On the output side, materials of adjustable stiffness and more advanced soft-mechanisms or additional integrated actuators and the use of *proportional valves* in the control system seem worthwhile to explore.

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