PneumoVolley: Pressure-based Haptic Feedback on the Head through Pneumatic Actuation

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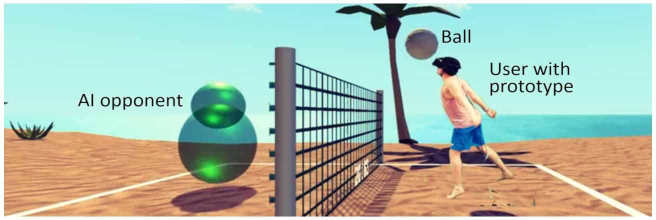


Figure 1: In-game screenshot of a user playing PneumoVolley against the AI opponent (greenscreen capture).

Abstract

Haptic Feedback brings immersion and presence in Virtual Reality (VR) to the next level. While research proposes the usage of various tactile sensations, such as vibration or ultrasound approaches, the potential applicability of pressure feedback on the head is still underexplored. In this paper, we contribute concepts and design considerations for pressure-based feedback on the head through pneumatic actuation. As a proof-of-concept implementing our pressure-based haptics, we further present PneumoVolley: a VR experience similar to the classic Volleyball game but played with the head. In an exploratory user study with 9 participants, we evaluated our concepts and identified a significantly increased involvement compared to a no-haptics baseline along with high realism and enjoyment ratings using pressure-based feedback on the head in VR.

CHI '20 Extended Abstracts, April 25–30, 2020, Honolulu, HI, USA.

ACM ISBN 978-1-4503-6819-3/20/04.
DOI: https://doi.org/10.1145/3334480.3382916

Author Keywords

Virtual Reality; Haptics; Pressure Feedback; Volleyball;

CCS Concepts

•**Human-centered computing** → **Human computer interaction (HCI);** *Haptic devices;* User studies;

Introduction

In recent years, Virtual Reality (VR) systems have become more affordable, and the ever-increasing level of detail of virtual worlds results in higher immersion [3] and presence [36]. While this trend is mostly attributable to advancements in visual and aural effects, haptic feedback is getting more into the focus for life-like experiences. Current research already adds a large spectrum of different haptic methods to reproduce the realistic impression of touch [35] or motion [12] through a variety of possibilities to create natural sensations, such as vibrotactile [17, 18, 13], Electrical Muscle Stimulation (EMS) [27, 25, 26, 31], thermal [14], and mechanical [10, 11, 5] approaches. However, EMS is not feasible for the use on the relatively muscle-less surface of the head, and mechanical approaches can restrict movements. Considering vibrotactile feedback on the head, actuators are often used for directional cues and spatial awareness [22, 21, 38, 6, 29, 2]. However, vibrotactile actuators have limitations to provide a realistic perception of pressure [21].

To overcome these limitations, air as a medium for touch [34], force-feedback [33], or hand-held controllers [37, 16], is used more frequently, and new methods for pressure-based feedback have been investigated. Delazio et al. [7] used compressed air to inflate air cushions on the body, while we inflated artificial muscles to actuate body joints for kinesthetic motion in a prior work [12]. While those approaches are well explored for the body (e.g., hands [28], arms [23], torso [7]), the application on the head is not yet fully explored. However, since the head has different properties compared to the rest of the body, other considerations for pressure feedback have to be investigated. For example, Rietzler et al. [32] use airflows to actuate local spots on the head for effects like wind or shockwaves. Kon et al. [24] use small inflatable cushions to simulate the *hanger* effect to trigger head-rotations and Chang et al. [4] propose motors on the HMD side to apply a shifting torque which resulted in an increased sense of presence.

In this paper, we propose concepts and design considerations for pressure-based feedback on the head. We further present a proof-of-concept implementation called *PneumoVolley*: a VR experience based on Volleyball played with the head to provide realistic impact forces through pneumatic actuation. In an exploratory user study, we investigated our concepts through a systematic evaluation with 9 participants.

Background

To sense different stimuli, the human somatosensory system covers sensations that directly interact with the skin or internals. While this comprises thermal, chemical, or pain stimuli, it also contains pressure mechanoreceptors: Merkel cells, Ruffini endings, and Meissner's corpuscles. While the latter is mainly sensing vibrations, Merkel and Ruffini corpuscles detect pressure on the epidermis and corium, and, thus, are most important for pressure [20]. Further, in contrast to the rest of the body, adipose tissue plays only a subordinate role due to the mostly bony and muscle-free structure of the cranium. However, the head can be very sensitive to an excess amount of external forces, described as scalp tenderness [8].

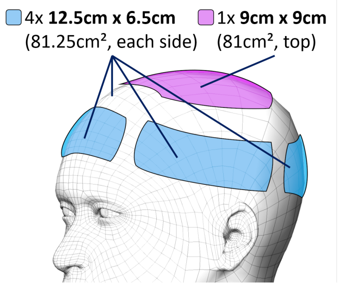


Figure 2: Layout and positioning of the air cushions on the user's head. We use four 12.5x6.5cm cushions on each side of the head, and one quadratical-shaped 9x9cm cushion on the top center of the head.

Pressure Feedback on the Head Concepts

Pressure-based feedback through pneumatic actuation is explored in various research [12, 7]. However, while existing research largely focused on limbs and torso, concepts to identify how such research applies to the different anatomy of the head has yet to be investigated, such as the amount of needed pressure, resolution, or interaction patterns. In the following, we present concepts and design considerations that we investigate for pressure-based feedback on the head.

Actuator Dimensions and Resolution

The size of the actuators has a decisive role in the design. Actuators can have a large enough size to cover maximum possible parts of the head or be small enough to be not perceived as disturbing. In particular, two factors have to be considered: 1) the surface size of the head, and 2) the resolution of the overall arrangement to stimulate separate and individual regions of the head.

Concerning the resolution, actuators should always be able to actuate the areas that are required for a specific application over a sufficiently large area. For example, if an application involves contact between the forehead and a surface, an actuator must also be available on the forehead. In general, the same rule can also be applied here: The higher the resolution, the more precisely the areas can be actuated accordingly. However, since a higher resolution requires more energy and potentially more surface area, pressure-based feedback can also rely on so-called phantom sensations which are often used for vibrotactile-based feedbacks [1, 30, 13]. In this case, it is possible to interpolate between two actuators by simultaneous applying pressure through the surrounding actuators with decreased pressure for each individual actuator.

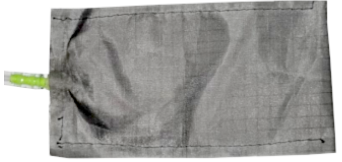
Applied Pressure

The pressure applied to the actuators on the head must be carefully considered as well. On the one hand, they should generate enough force so that acting forces in VR are reproduced as realistically as possible. On the other hand, unpleasant effects such as pain or irritation should be avoided. In existing research, most explored parts of the body have a strong buffer of adipose tissue and musculature between the skin and the skeleton, which can compensate the effects of pressure and be operated safely with 300+ kPa without negative effects on the user (e.g., [7, 12]). For the head area, however, these large fat and muscle buffers do not exist and as a hypothesis, we assume that too much pressure stimulates the nerve cells of the skin much more directly. Further, under no circumstances should any damage occur to the brain cells which can already occur from head balls during soccer matches [9, 15]. Thus, it has to be investigated if smaller amounts of pressure are already sufficient to represent an impact-force realistically and harmlessly.

Interaction Patterns

Interaction patterns allow for different perceptions and reactions to the triggered haptic stimuli and the head can be actuated through different methods. On the one hand, there is a very simple, but direct and binary possibility to stimulate the skin beneath by applying pressure through an air cushion on a specific position (e.g., contact with surfaces, external forces, pressure on/off). On the other hand, in contrast to this, there is also the possibility to display different (indirect) interaction patterns that represent specific events or occurrences, such as notifications or directional cues. Hereby, the number of interaction patterns is largely unlimited and ranges from simple rotations (adjacent actuators inflate and deflate one after another) to pulsations (actuators inflate and deflate in a wave-like

(a) deflated



(b) inflated

Figure 3: Actuator cushions in (a) deflated, and (b) inflated state.

Figure 4: Prototype cap with four cushions on each side (blue) and one actuator cushion on the top center (purple).

pattern over a certain period), to complex stimulation sequences, e.g. the combination of pulsation and rotation. In such a case, the resolution has to be considered again for a perception of fluid actuations. However, it could be simplified by the use of phantom sensations [1].

PneumoVolley System

To investigate our design space, we implemented a proof-of-concept prototype with five individual actuator cushions that can address five different areas of the head: left, right, front, back, and top of the head (see Figure 2). After informal tests, we decided on two different actuator sizes with different lengths and widths but the same volume (each 81 cm^2). Four actuators have the dimensions of 12.5 cm × 6.5 cm each and are located in a ring on the longitudinal cross-section of the head (left, right, front, back). At the center of the head, however, elongated actuators are not optimal, and we opted for a square cushion (9 cm × 9 cm). All actuators are attached to the inside of a fabric cap with velcro and can be positioned precisely for varying head sizes as depicted in Figure 4.

For our system, we set the applied pressure to 250 kPa (2.5 bar) using a standard air compressor[1]. We use 12V solenoid valves[2] mounted between 5 m long PVC tubes (4mm diameter) and the compressor to control each actuator individually. The system uses an ESP-32 microcontroller that communicates via a serial connection with the application computer, allowing each event (e.g., ball contact) to trigger actuators fully dynamically. Switching a solenoid valve takes 30 ms and actuators can be inflated as long as needed (e.g., for the impact of a ball, we use an inflation duration of 150 ms). An actuator while deflated and inflated is depicted in Figure 3.

PneumoVolley Game

PneumoVolley is an interactive ball game in which the player has to play a ball to the other side of the field with the head. It is implemented in Unity[3] and uses the Valve Index[4]. The game is based on the open-source *Blobby Volley*[5] head-to-head 2D-game from 2001 with derived rules from Volleyball. If the ball lands on the ground of the opponent, the player receives a point; and vice-versa. The player can move around freely within his side but is only allowed to reach the ball with the head a maximum of three times per ball rally. Otherwise, it is a foul and the opponent receives a point. Unlike in classic Volleyball, the ball never gets out of bounds since solid walls around the playable area bounce the ball back. The first player to score 15 points wins.

The size of the playing court is dynamic and adapts to the VR tracking space. To avoid collisions with the environment, there is enough free space to walls and other obstacles. In our case, the area of the player's half of the court has a size of 3x2 m and an additional minimum distance of 1.5 m to any obstacles. An in-game screenshot is depicted in Figure 1.

PneumoVolley has two modes: 1) 2-Player Multiplayer, and 2) Singleplayer AI-Mode. In multiplayer, two players can compete against each other using either their own VR tracking spaces (with optional pressure-feedback), or play traditionally using a keyboard (no haptics).

In singleplayer, the opponent is an AI-based non-player character trained using Unity's ML Agents [19] with the

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[1] Dürr Technik TA-200K, up to 12 bar, 25 liter volume

[2] U.S. Solid G12V DC solenoid valve, up to 7 bar, normally closed

[3] https://unity.com, last accessed 2020-01-06

[4] https://www.valvesoftware.com/en/index, last accessed 2020-01-06

[5] https://github.com/danielknobe/blobbyvolley2, last accessed 2020-01-06

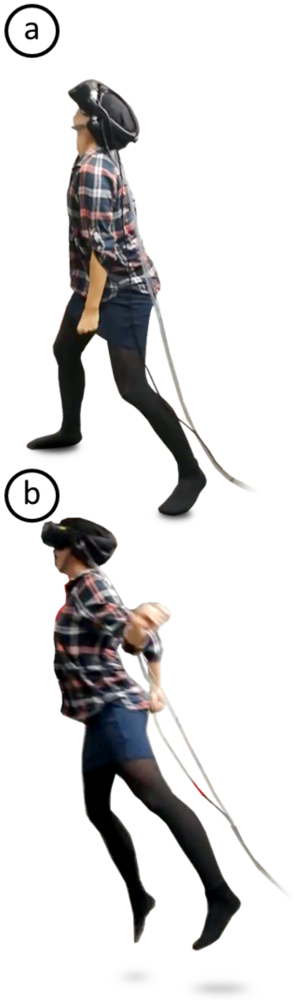

Figure 5: A participant during the study (a) preparing and (b) performing a jump to reach the ball in VR.

Proximal Policy Optimization reinforcement learning algorithm (currently, thirty simultaneous instances with a total of fifty million steps). The Learning Agent could move the character on two axis (forward/backward, left/right) and trigger jumps. To learn the rules, the agent got rewarded for each ball played over the net, and penalties if the ball touched the own half or had more than three contacts. Afterward, the ball was returned to the AI randomly.

User Study

We evaluated our system with regards to presence, enjoyment, and realism in an exploratory study with 9 participants between 21 and 62 years (M=35.7, SD=13.6, 4 female, 5 male). Four participants had no VR experiences, four had some experiences, and one uses VR regularly.

We used a within-subjects design and participants played in singleplayer mode against our AI. As our independent variable (IV), we used the haptic actuation with two levels: 1) no-haptic baseline, and 2) pneumatic haptic feedback where ball contacts result in localized pressure on the head. All conditions were counterbalanced.

Before starting the first condition, we explained the concepts and game rules. We then asked to sign a consent form and assisted putting on the HMD and prototype. Once ready, participants could start playing the game (Figure 5). After each condition, we used a subset of the Witmer-Singer questionnaire [36] focusing on involvement and haptic factors to quantitatively assess the presence. In addition, we also asked how engaging and realistic the pressure-based feedback was perceived and how participants enjoyed the overall experience in a final questionnaire (all 7-Point Likert scales). Afterward, we asked for additional qualitative feedback.

Results

We performed a non-parametric analysis of our Likert questionnaires' results using Wilcoxon rank-sum tests for our pairwise post-hoc analysis. Further, we report the mean values and the standard deviation of each.

How involved were you in the Virtual Environment experience? There were significant higher scores for our pressure-based feedback ($M = 5.44$, $SD = 0.88$) compared to the scores of the no-haptics baseline ($M = 4.56$, $SD = 1.42$) with regards to the involvement in the VR experience; $Z = 0.00^6$, p <.05 (see Figure 6a).

How much did your experiences in the Virtual Environment seem consistent with real-world experiences? The pressure-based feedback had favorable higher scores ($M = 4.00$, $SD = 0.70$) compared to the no-haptics baselines ($M = 3.11$, $SD = 1.27$), however, our analysis did not reveal any significant differences; $Z = 2.50^7$, p >.05 (see Figure 6b).

How responsive was the environment to actions you initiated? While both conditions resulted in high scores for the responsiveness (baseline: $M = 4.22$, $SD = 1.30$, pressure: $M = 4.56$, $SD = 1.01$), the analysis did not reveal any significant differences; $Z = 15.50^8$, p >.05 (see Figure 6c).

How realistic did you find the additional haptic feedback? We asked the participants to rate the realism of the overall haptic experience while playing the game. Here, participants constantly rated the pressure-based haptic addition with high scores ($M = 5.0$, $SD = 1.69$).

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[6] 3 pairs of values were tied
[7] 2 pairs of values were tied
[8] 2 pairs of values were tied

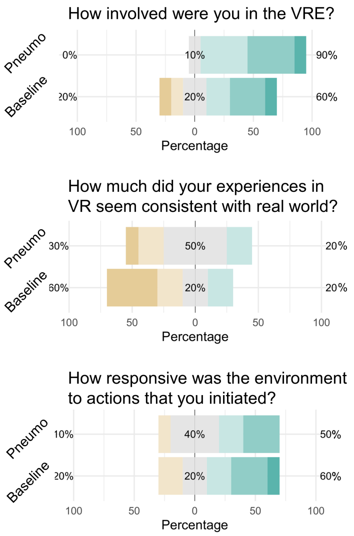

Figure 6: Results of the Witmer-Singer questionnaires regarding (a) involvement, (b) real-world consistency, and (c) responsiveness.

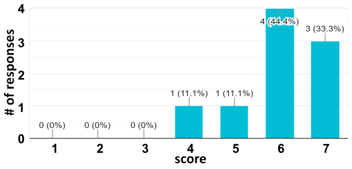

Figure 7: User rating of the overall enjoyment.

Acknowledgements
We thank all participants for their valuable support. This work was funded by DFG under No. 21150064.

How much did you enjoy the overall experience?
In a final question, we asked for the overall enjoyment of the haptic VR experience. The scores show a very high enjoyment of the participants while playing ($M = 6.0$, $SD = 0.94$, see Figure 7) which supports our other findings indicating that our pneumatic-based pressure feedback is a viable addition for VR experiences.

Qualitative User Feedback
The participants provided additional qualitative feedback and agreed that they enjoyed the experiment, appreciating the pressure-based feedback on the head as “fun VR experience” (P3, P7). They also were positive about the “implementation of the haptic feedback” (P5) and that the “air cushions give very localized feedback where it hit my head or if I even hit it” (P2). Moreover, P1, P4, and P9 stated the feedback “could have been stronger”, contrary to our assumption that less pressure than in existing approaches is enough. No participant felt uncomfortable or had the impression the impact forces were too hard. One participant even explained that “the cap was comfortable which I did not expect before” (P9)

The overall game was described as “fun” (P5) with “nice visuals” (P6) and “good competitive gameplay” (P8). One participant remembered the original BlobbyVolley game and described it as “nostalgic experience” (P4). While participants only played against an AI opponent, some described the AI as too “immature” (P6) and sometimes too “unfair” (P5). Also, participants did express that the playing area was “too small” (P3, P6), and the “ball behavior sometimes feels unrealistic” (P2). As a further improvement, P2 suggested adding hand visualizations which we intentionally excluded from the study.

Discussion and Limitations

Our results show the feasibility of pressure feedback on the head through a proof-of-concept implementation. Significant higher scores for involvement compared to the no-haptics baseline and a high enjoyment show a clear trend for the positive effects, supported by the users’ feedback. Although there were no significant effects on the consistency with real-world experiences, participants rated the pressure feedback as realistic. However, contrary to our assumption that less pressure on the head is more reasonable, some participants would even increase the amount of pressure applied.

We presented design considerations for pressure feedback on the head along with a demo application, however, but currently only investigated very direct feedback in the form of ball contact. Hence, for future experiments, we plan to vary timings and intensities for different interaction patterns, as well as to increase the number of actuators for a higher resolution.

Further, we plan to investigate potential extensions for other VR scenarios beyond entertaining applications, such as notifications, directional cues, or simulating emergency tasks. Also, while no participant felt it was an obstacle, increasing wearability by using a wireless HMD and having a backpack with small cartridges to supply compressed air is planned for future studies.

Summary

In this paper, we contributed concepts for pressure feedback on the head and presented PneumoVolley: a proof-of-concept VR experience. In a first experiment, we investigated the applicability of our concepts and showed a significantly higher involvement compared to no-haptics along with a high rating of realism and enjoyment.

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