PneumAct: Pneumatic Kinesthetic Actuation of Body Joints in Virtual Reality Environments

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Figure 1. We propose a pneumatic actuated jacket for kinesthetic motion of body joints in Virtual Reality Environments.

ABSTRACT
Virtual Reality Environments (VRE) create an immersive user experience through visual, aural, and haptic sensations. However, the latter is often limited to vibrotactile sensations that are not able to actively provide kinesthetic motion actuation. Further, such sensations do not cover natural representations of physical forces, for example, when lifting a weight. We present PneumAct, a jacket to enable pneumatically actuated kinesthetic movements of arm joints in VRE. It integrates two types of actuators inflated through compressed air: a Contraction Actuator and an Extension Actuator. We evaluate our PneumAct jacket through two user studies with a total of 32 participants: First, we perform a technical evaluation measuring the contraction and extension angles of different inflation patterns and inflation durations. Second, we evaluate PneumAct in three VRE scenarios comparing our system to traditional controller-based vibrotactile and a baseline without haptic feedback.

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INTRODUCTION
With improving quality of Head-Mounted Displays (HMDs), Virtual Reality Environments (VREs) are becoming increasingly immersive [1] and are leading to a higher perception of users' presence [50]. While this is mainly due to the high degree of detail in the visual and auditory channel, the haptic channel is the most limiting factor why we have not reached Sutherland's vision of the ultimate display [53] yet. As state-of-the-art systems (e.g., the HTC Vive) are still using vibrotactile haptic feedback emitted through hand-held game-controllers, research projects are constantly proposing new ways to improve the haptic experience by, e.g., adding haptic properties to the user's environment [4, 21, 29], adding active haptic feedback to hand-held controllers [5,40,60], or directly onto a user's body [12,19,31,36,37]. Considering the technologies that are used for creating these haptic sensations in VREs, most body-worn systems use either vibrotactile actuators [22,23,52], Electrical Muscle Stimulation (EMS) [36,37,38,43], or mechanical peripherals like exoskeletons [15,17] or external muscles [3].

Additionally, previous research also suggested using compressed air for creating haptic sensations in the environment and on users' bodies. Previously introduced stationary systems create air vortexes to provide on-body tactile sensations [20, 51] or use continuous air streams to create force feedback in VREs [54, 55]. Recently, Delazio et al. [12] used compressed air for on-body pressure feedback in VREs.

Further, there exist a large variety of pneumatically actuated exoskeletons based on Pneumatical Artifical Muscles (PAMs) which were introduced in the 1950s. Their application areas reach from the support of users to use and lift heavy objects [48, 58], to medical prostheses [27, 59], or for supporting stroke rehabilitation [8, 9, 46]. Interestingly, these PAMs can create a unique haptic sensation by varying the air pressure and the pattern in which the compressed air is emitted, e.g., of the user's hand [11, 41]. However, until today, these PAMs have not been used for creating haptic force feedback and kinesthetic motion in room-scale Virtual Reality (VR), yet.

In this paper, we are closing this research gap by introducing the "*PneumAct*" system, which elicits direct kinesthetic motion and movements of users' body joints using PAMs and air cushions (cf. Figure 1). For this, *PneumAct* uses two types of actuators, the *Contraction Actuator* (CA) and the *Extension Actuator* (EA), which lead to two opposed movements of body joints. This enables novel possibilities for providing kinesthetic body motion in VR that can be used in a large variety of scenarios, such as entertainment, training motor skills, or ergonomics support to correct unhealthy body postures.

The contribution of our paper is two-fold. First, we present the *PneumAct* system for providing haptic feedback in VREs using PAMs by presenting a proof-of-concept prototype: a pneumatically actuated kinesthetic jacket. Second, through two user studies with a total of 32 participants, we performed a technical evaluation of *PneumAct* to investigate the effects of different inflation patterns and durations of the actuators. Based on the results, we conducted a second user study comparing our *PneumAct* jacket to state-of-the-art game-controller-based vibrotactile feedback and a non-haptic baseline in three VR applications.

RELATED WORK

Haptic feedback has come a long way, and research identified multiple ways to enable haptic feedback in virtual worlds. The three most known are 1) vibrotactile, 2) Electrical Muscle Stimulation (EMS), and 3) exoskeletons that all have the advantage to actuate the human body to provide a haptic sensation. However, more work is emerging that leverages the actuation through 4) pneumatic systems using an air flow (e.g., [12, 20, 54]). In the following, we use the categorization from above and give an overview within the scope of this paper.

Vibrotactile

A mostly low-cost approach is the usage of vibrotactile actuators, such as small vibration motors or solenoids [34]. For example, Israr et al. [22, 23] explored the effects of full-body haptic feedback through vibrotactile actuation. In more recent work, Konishi et al. [31] presented a vibrotactile suit that embeds 24 vibration motors to actuate the whole upper body of a user in VR. Further, there are commercial or crowdfunded vibrotactile systems available or in development, such as Tactsuit[1], KOR-FX[2], Hardlight VR suit[3], or the neosensory vest[4]. However, those approaches are focusing on tactile feedback rather than providing kinesthetic motion and encoding.

Therefore, Spelmezan et al. [52] introduced tactile patterns for full-body motion guidance. Günther et al. [18] used vibrotactile stimulation to guide a user's hand towards a specific target, while Kaul et al. used a similar approach for the head [24, 25]. Moreover, such actuations can also be used to add another layer of feedback that gives the impression of being something else. For example, Kurihare et al. [32] put vibrotactile actuators on body joints to simulate the impression of being a robotized human. However, while practical and useful, vibrotactile sensation is limited since it is mostly indirect and users have to learn vibration patterns to follow instead of a kinesthetic actuation.

Electrical Muscle Stimulation (EMS)

A possible solution to induce kinesthetic motion directly to the body is the usage of EMS. Compared to vibrotactile feedback, EMS does not only allow the stimulation of the skin but also actively creates muscle tension through electric impulses coming from surface electrodes, thus, resulting in body movements and motion. For example, Pfeiffer et al. [43] created a wearable EMS kit for easy to set up force feedback. Similar, Lopes et al. [35, 36] uses EMS to actuate the body in terms of force and physical impact which can actively manipulate a user's motion. Based on that, Lopes et al. [37, 38] extended this idea and added such force feedback through EMS in Virtual and Mixed Reality scenarios, such as gaming applications. Here, the electric stimulation was used to simulate the impression of weight or counterforce limiting or enhancing the user's motion.

Exoskeletons

The third category of well known haptic feedback is to use an external force in the form of exoskeletons. For example, Dollar et al. [13] gave an overview of state-of-the-art technologies with regards to lower extremity exoskeletons that support walking and similar movements.

[1] https://www.bhaptics.com/tactsuit/, accessed 2019-01-18
[2] http://korfx.com/products, accessed 2019-01-18
[3] https://www.kickstarter.com/projects/morgansinko/hardlight-vr-suit-dont-just-play-the-game-feel-it/description, accessed 2019-01-18
[4] https://neosensory.com/vest/, accessed 2019-01-18

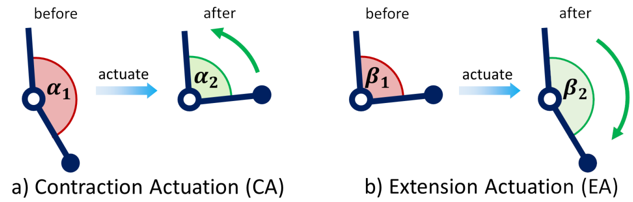


Figure 2. Conceptual actuation of body joints for a) contraction, and b) extension movements. α illustrates the angle change in form of a contracting flexion, while β illustrates the angle change of an extension movement.

Further, Fick et al. [14] presented a full-body exoskeleton in 1971, which supports workers in executing tasks. While early versions were still bulky, modern systems are getting increasingly lightweight and researchers, such as Frisoli et al. [15], explored their potential in VR. While highly effective, those systems are, however, often still too big for personal use at home, and cost-intensive. To overcome these high-costs, Gu et al. [17] presented Dexmo which provides an inexpensive hand exoskeleton for force feedback in VR. Similar, Chen et al. presented a motion guidance sleeve that uses an external artificial muscle made of strings to control the forearm rotation [3]. While they consider the wrist rotation, it does not actuate larger movements, such as flexing an arm.

Pneumatic and Air

Recently, the usage of pneumatics and air to actuate the body or to provide a tangible layer [61] evolved which can be used similarly to other haptic actuations. For example, as notifications [26, 44], to provide tactile feedback for users (e.g., through air vortexes [20, 51]), or similar to exoskeletons (e.g., to assist walking [42] or supporting a person's force [48]).

Delazio et al. [12] designed a haptic jacket that contains several air cushions to provide pressure feedback in VR called Force Jacket. Each pneumatic actuator can be inflated and deflated individually to simulate the effects of impacts, touches, or even vibration through fast actuations. Using a similar principle, the commercial haptx[5] glove uses tiny actuators to provide touch sensations on the fingers. However, while both systems are highly relevant and are using the same medium as *PneumAct* (compressed air), they focus on pressure feedback on the skin and do not cover kinesthetic motion actuation.

In contrast, Raitor et al. [47] presented a wearable wristband that uses pneumatically actuated patterns to encode hand rotation and translation. However, those only provided an indirect stimulation similar to vibrotactile systems. A more direct manipulation was done by Moon et al. [41] who compared a pneumatic and hydraulic based glove in a VRE and by Das et al. [11] and Goto et al. [16] who created pneumatic and gel-based systems to actuate the user's wrist motion. Other work [33, 57] presented and surveyed actuation gloves for VR systems, while similar works presented pneumatically actuated gloves for stroke rehabilitation to actuate single fingers of users (e.g., [8, 9, 30, 46]). However, all of them focused on (stroke) rehabilitation for the hand and wrist, and did not explore immersion aspects or other body parts.

[5] https://haptx.com/, accessed 2019-01-18

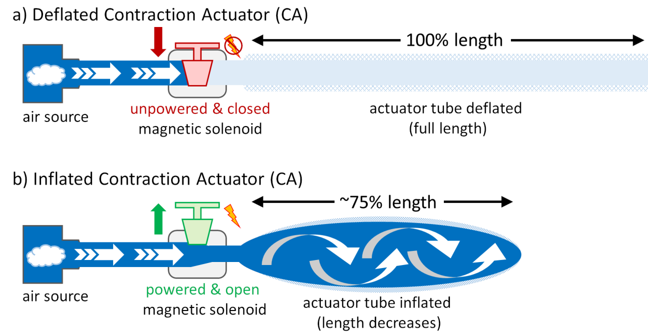


Figure 3. Function principle of our Contraction Actuator. a) In a deflated state, the air flow coming from an air compressor is blocked by a magnetic valve. b) As soon as the valve is powered, it opens and the air flow fills the actuator which results in a decreased length.

Also, compressed air can be used on body joints to inherit movements of the user [45], or even to limit motion entirely if an actuator is vacuumized as shown by Maimani et al. [39]. However, to the best of our knowledge, there is no research done on kinesthetic motion of body joints through pneumatic actuation in room-scale VREs and, thus, is still underexplored.

PNEUMACT

In this paper, we present *PneumAct* that provides kinesthetic motion of body joints in VRE through pneumatic actuation.

Actuators

In order to kinesthetically actuate body joints and other parts of the human body, we need to consider different types of actuators that adapt to natural behaviors. Here, we defined two different types of actuators: 1) a *Contraction Actuator* (CA) that decreases the angle around a body joint, and 2) an *Extension Actuator* (EA) that does the opposite by increasing the angle. For example, to perform a flexion of the arm, a user has to contract the biceps resulting in a motion of the forearm towards the upper arm and, thus, decreasing the angle between those body parts. On the other hand, if a user performs an extension of the arm, the triceps forces the forearm to move away from the upper arm which results in an increased angle (cf. Figure 2).

Contraction Actuator (CA)

To let users perform a flexion of a body joint, we need an actuator that is able to *pull* or *contract* limbs and reduce the angle between them. Therefore, we utilize the concepts of a Pneumatical Artifical Muscle (PAM)s which can be pneumatically actuated to reduce its size (cf. Figure 3). PAMs, also known as McKibben muscles, were already invented in the 50's [6, 28, 56] and are well established for the use in robotics or exoskeletons [2, 10].

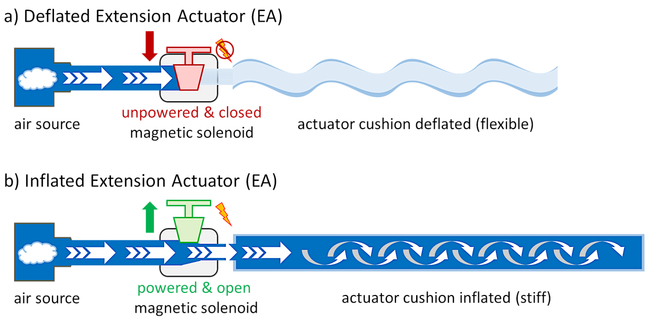


Figure 4. Function principle of our Extension Actuator. a) In a deflated state, the air flow is blocked and the pad has no stiffness that would limit the user's movements. b) As soon as the valve is powered, it opens and the air flow fills the actuator which results in a high stiffness pushing body parts into a linear position.

Such artificial muscles consist of a flexible latex tube embedded in a slightly larger mesh tube. If compressed air is inflating the actuator (e.g., by opening a valve), pneumatic energy acts in the form of pressure on the inner tube and is converted into mechanical energy by the physical limitation of the outer shell. As a result of the applied pressure, the diameter of the actuator expands, while at the same time it contracts lengthwise and, thus, reduces its length, as depicted in Figure 3. We use this concept and mount this actuator around a body joint. The resulting tensile force then flexes or bends the connected limbs.

We use a $50cm$ long tube with a $0.8cm$ diameter for our CA since this fit a typical adults' arm lengths. When fully inflated, we could identify a maximum decrease in length of $\sim 24\%$ (12 cm), and an almost doubled diameter of $1.5cm$. Further, we measured a maximum initial force of up to $150N$ (approx. $15kg$).

Extension Actuator (EA)

In order to support the extension of the angle between limbs, we need an actuator that can increase in size and changes stiffness. For this, we designed flat air cushions which are positioned at the bending point of a body joint, such as the crook of the elbow. Both short ends of the air cushion are attached to one connected limb, e.g., the forearm and upper arm. If air is now inflating the actuator, it causes the air cushion to push the attached ends apart and, thus, ensures an increased angle at the corresponding position of the body joint.

Different from the CA, the Extension Actuators are made of synthetic fabric, cut to rectangular shapes and folded into air cushion. All sides of the material are glued to prevent air from escaping. To inflate the actuators with compressed air, we added a small opening at the lower end of each actuator and attached a PVC hose. Our final EA has a size of $17.5cm \times 5.5cm$ and inflates up to a diameter of $3.5cm$. The functionality of this actuator is depicted in Figure 4.

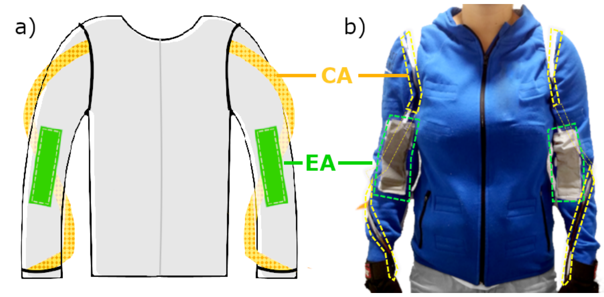


Figure 5. Our wearable jacket embedding both of our actuators as a) concept, and b) finished prototype. The *Contraction Actuators* are mounted on the outside of the jacket and wrapped around the arms (yellow). The *Extension Actuators* are located at the crooks of the elbows (green).

PneumAct Jacket

We built two actuators of each type and embedded them in a slim-fit fabric jacket. The CAs are wrapped around the arm sleeves while one end is fixed around the shoulder with an adjustable strap. The other end can be attached to the user's hand or wrist to fit different arm lengths since it is essential that the CAs are always fixed tightly to the arms. The EAs have to be located at the crook of the elbow. Therefore, we use Velcro on the related sleeve position and, if necessary, can re-locate the EAs accordingly (e.g., for larger or smaller persons).

Further, we designed the whole jacket including the actuators as comfortable as possible as it should not constrain any natural movements. Also, while being able to actuate the users' arms, it is still easy to counteract since forces only apply in natural movement directions to prevent overshooting. In Figure 5, we show a conceptual image of the location of each actuator, as well as a picture of a user wearing our final *PneumAct* jacket.

Actuation Control Unit

We built a separate control unit using off-the-shelf electronic components to control the inflation and deflation of the actuators. We used an ESP32-ST microcontroller which provides a communication interface via USB or Bluetooth LE (cf. Figure 6 b)). We used an air compressor (*Einhell TH-AC 200/24 OF*) that supplies up to $8bar$ ($800kPa$, $116.0psi$) of pressure (see Figure 6 a)). However, we regulated the pressure to $5bar$ ($500kPa$, $72.5psi$) since pretests showed no noticeable advantages at higher levels. The compressor was connected to an

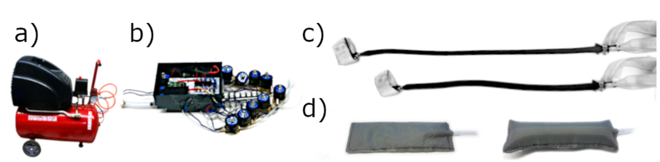


Figure 6. Picture of all components besides the jacket showing a) the air compressor, and b) the circuit board with the magnetic valves. Further, it shows the inflated and deflated state of the c) CA, and d) EA.

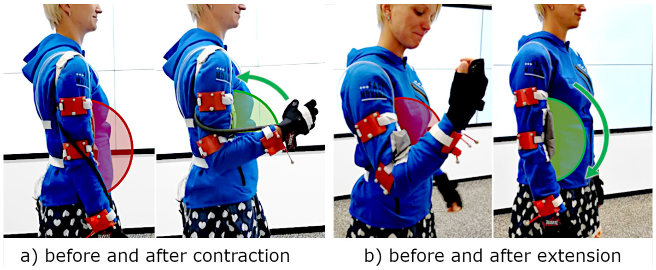


Figure 7. Picture of a participant during the technical evaluation with a) the *Contraction Actuator* (CA), and b) the *Extension Actuator* (EA) before (left) and after each actuation (right).

air distributor, and ten normally-closed solenoid valves (*U.S. Solid JFSV00051*) were attached to the output pipes. One was used as the main valve to regulate the air flow between the compressor and air distributor while another valve was used to release excess air from the system, reducing pressure inside the system. The remaining valves were linked directly to the actuators via flexible tubes.

Since the valves are in a normally-closed state, we had to apply power to inflate an actuator. For this, the microcontroller regulated the 12V DC power supply by switching MOSFET transistors (*IRLZ34NPBF*), and once the microcontroller received a command to inflate one of the actuators, it opened the respective valve together with the main valve. This kept the pressure level inside the system low if no actuator is active and also allowed to open the deflation valve without losing compressed air. Additional safety diodes (*1N4007*) were added to each valve to protect the hardware from reverse voltage spikes and currents when losing power. A detailed circuit diagram can be found in the supplementary materials.

Each actuator can be controlled manually, or entirely automatically through dynamic in-application events using our Unity compatible *C#* API (e.g., using colliders, user position changes, or other custom events, such as timed triggers).

Safety
While the system operates at $5bar$, it is always possible to counteract, and forces only apply in natural movement directions with physical safety methods to prevent overshooting. We also added hard- and software switches to immediately release air from the system.

STUDY I: TECHNICAL EVALUATION
We evaluated how our proposed *Contraction Actuator* (CA) and *Extension Actuator* (EA) affect the angle of a user's arm (cf. Figure 7). Hereby, we investigated the following research questions:

1. How does the inflation *duration* affect the angle?
2. How do inflation *patterns* affect the angle?

Study Design
We used a repeated-measure design in order to answer the questions above. Therefore, as the dependent variable, we measured the change of the angle between the forearm and upper arm. Further, we defined two independent variables (IV): 1) the inflation *duration*, and 2) the inflation *pattern*. In addition, we counterbalanced the actuation (EA and CA), and side of the arm through a Balanced Latin square design. Since both types of actuators have different behaviors, we defined different levels for both independent variable (IV)s. To support the readability, we describe the levels of the IV separately for both actuator types in the following.

Contraction Actuator (CA)
We defined four levels of the inflation *duration*: 1) 100 ms, 2) 200 ms, 3) 300 ms, and 4) 400 ms. We selected for 100 ms as lower bound since informal pre-tests showed only a very small actuation. Similarly, we used 400 ms as an upper bound because the actuator did not inflate any further afterward.

For the inflation *pattern*, we defined five levels: 1) continuous inflation, 2) 50-50, 3) 50-100, 4) 100-50, and 5) 100-100. Apart from the continuous inflation, the first numbers always indicate a single inflation duration, while the second numbers indicate the pause duration until the next inflation (either $50ms$ or $100ms$) as depicted in Table 1. In addition, we fitted the number of intervals for each *pattern* with regards to the total inflation *duration*.

Each combination was repeated six times (three on the left arm, three on the right) which resulted in a total of $4 \times 5 \times 6 = 120$ trials.

Level	contin.	50-50	50-100	100-50	100-100
Pattern	■■	■—	■——	■■—	■■——

Table 1. All five levels of the inflation *patterns* (including continuous and intervals inflations) during the contraction condition. ■ represents a single inflation of 50 ms, — an interval pause of 50 ms.

Extension Actuator (EA)
The EA behaves slightly different from the CA. Therefore, we had to adjust the levels of our IVs. We defined three levels for the inflation *duration*: 1) 50 ms, 2) 100 ms, and 3) 200 ms. This time, we used 50 ms as lower, and 200 ms as upper bound since the inflation had almost unnoticeable effects below and did not inflate any further above.

Again, we defined five levels for the inflation *pattern*: 1) continuous inflation, 2) 25-50, 3) 25-100, 4) 50-50, and 5) 50-100. Again, apart from the continuous inflation, the first numbers indicate the single inflation durations, while the second numbers indicate the pause durations until the next inflation as depicted in Table 2. Due to the technical limitation of the magnetic valves which cannot open faster than 20 ms, and close faster than 30 ms, we used a minimum single inflation duration of 25 ms. As

Level	contin.	25-50	25-100	50-50	50-100
Pattern	■■	■——	■————	■■——	■■————

Table 2. All five levels of the inflation *patterns* (including continuous and intervals inflations) during the extension condition. ■ represents a single inflation of 25 ms, — an interval pause of 25 ms.

before, we fitted the number of intervals for each *pattern* with regards to the total inflation *duration*.

Each combination was repeated six times (three on the left arm, three on the right) which resulted in a total of $3 \times 5 \times 6 = 90$ trials.

Task

To compare how the *duration* and *patterns* affect the actuation, we designed a task where participants had to wear both of our actuators on their left and right arm. However, we only actuated either the CA or the EA during one condition. Also, we either only actuated the left or the right arm in one condition, resulting in four conditions in total. In all of them, participants had to put their arms into relaxed starting positions: during contraction actuation, the arm had to hang downwards; during extension actuation, the lower arm had to be angled comfortably facing upwards. For both, we told the participants to relax their arms and to not push against the active actuation. However, they could stop their motion once they think the actuation is over. Afterward, we kept the air inside the current actuator for one second. After rereleasing the air, participants had to bring their arm back to the starting position.

Setup and Apparatus

Each participant had to wear our *PneumAct* jacket, where we mounted the CA tightly around the left and right arms. The EA were positioned at their crook of the elbow as depicted in Figure 5.

We tracked the participant's position, the current angle between the forearm and upper arm, a timestamp, the current condition, and the trial number. For this, we used an optical tracking system[6] with retro-reflective markers attached to the upper arm, the elbow, and the forearm mounted on custom 3D-printed plates as depicted in Figure 7. All trackers including the 3D-printed parts did not restrict movements or the actuation as they were placed at non-disturbing positions.

Procedure

After welcoming the participants, we gave them a short introduction to our concepts and introduced them to our *PneumAct* jacket. We detailed the study's data protection policy and informed the participants about safety precautions which align with the guidelines of the ethic's committee at our institution. We then proceeded by explaining the consent form, that each participant had to sign, and asked the participants to fill out a demographic questionnaire including their age, height, dominant hand, and straightened arm length (measured starting from the shoulder to the bone of the wrist). In a final step, we assisted by putting on the actuators and tracking markers at the correct positions and assured that the jacket was comfortable for the participants.

Following, we told the participants to stand at a predefined location and to angle the arms in a starting position. During the contraction task, the arms had to face towards the floor in a relaxed way, resembling approximately 180° between the forearm and upper arm. While testing the extension, participants were instructed to bend the arm as far as possible; however, without applying any pressure.

We then started the trials with the arm in the starting position corresponding to the extension or contraction task. Our system then randomly selected one of the conditions and inflated the current actuator respectively as shown in Figure 7. After a second holding time, we released the air, and the participants had to put their arm back into the starting position. In order to prevent participants from preparing temporally for an upcoming actuation, we also randomized the time intervals of two trials between 1 and 3 seconds until the arm returned to the starting position.

After finishing a condition, participants could take a short break to relax their arm. Once they were ready again, we continued with the next task until all conditions were done. During the whole experiment, we encouraged participants to provide qualitative feedback at any time. In total, the study took 40 minutes per participant.

Participants

We recruited 24 participants (10 female) between 21 and 35 years (M=26, SD=3.6). All of them used their right hand as dominant hand and had an average arm length of $55cm$ ($SD = 4.6cm$, measured from shoulder to wrist). Apart from snacks and drinks, we did not provide any compensation.

Quantitative Results

We used a repeated-measures ANOVA to analyze our data statistically. We tested the data for normality with Shapiro-Wilk's test and used Mauchly's test to check possible violations of the sphericity assumption. If the sphericity was violated, we used the Greenhouse-Geisser correction for adjusting the degrees of freedom and report the ϵ value. If we identified significant effects, we used a Bonferroni corrected pairwise t-test for post-hoc analysis. We report the effect size as eta-squared η^2 using Cohen's classification categorizing the effect size as small, medium, or large [7]. Further, we report the Estimated Marginal Mean (EMM) as an estimated influence of individual factors [49].

[6]OptiTrack http://optitrack.com/, accessed 2019-04-17

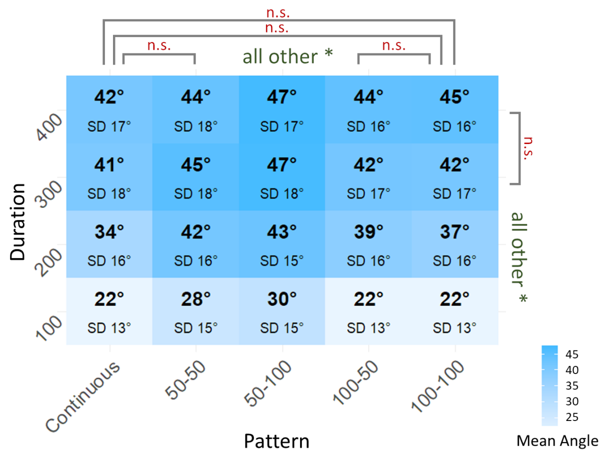


Figure 8. Angle changes for different *durations* and *patterns* while inflating the CA. If not indicated with *n.s.*, all conditions have significant differences.

For better comprehension, we subdivide the quantitative results between both types of actuators. First, we present the results for the CA, followed by the EA's results. To conclude this section, we further present the combined qualitative feedback given by the participants.

Contraction Actuator

Our analysis revealed a significant effect of the *duration* with a large effect size ($F_{1.68,38.76} = 101.53$, $p < .001$, $\epsilon = 0.562$, $\eta^2 = 0.188$). We could identify a significant increase of the angle between all *durations* of 100 ms, 200 ms and 300 ms (all $p < .01$). We could not find any significant effect between 300 ms and 400 ms (EMM_{300} $\mu = 43.4°$, $\sigma_{\overline{x}} = 3.12°$, EMM_{400} $\mu = 44.3°$, $\sigma_{\overline{x}} = 3.12°$, $p > .05$).

We could also identify significant effects of the *pattern* with a small effect size ($F_{2.46,56.64} = 16.05$, $p < .001$, $\epsilon = 0.616$, $\eta^2 = 0.02$). Regarding the difference of the arm angles, we found that *continuous* inflations always resulted in a smaller mean angle difference than inflations with the same *duration* but different patterns. We could observe that *patterns* with short bursts of 50 ms (*50-50* and *50-100*) resulted in the largest angles ($p < .001$ for both and a *continuous pattern*, as depicted in Figure 8).

Extension Actuator

The analysis indicated significant effects for the *duration* ($F_{1.19,27.42} = 74.29$, $p < .001$, $\epsilon = 0.596$, $\eta^2 = 0.235$) with a large effect size. Post-hoc tests revealed always significant increasing angles for longer *durations* (EMM_{50} $\mu = 13.7°$, $\sigma_{\overline{x}} = 4.1°$, EMM_{100} $\mu = 29.6°$, $\sigma_{\overline{x}} = 4.1°$, EMM_{200} $\mu = 42.3°$, $\sigma_{\overline{x}} = 4.1°$; all $p < .001$).

Further, our analysis indicated significant effects for the different *patterns* with a small effect size ($F_{2.1,48.4} = 46.79$, $p < .001$, $\epsilon = 0.526$, $\eta^2 = 0.046$). Similar to the CA, the post-hoc tests revealed significant larger angles between *continuous* inflations and interval *patterns* ($p < .001$). Again, the shortest *patterns* (25-50 and 25-100) resulted in the significantly largest angles (all $p < .001$). A detailed comparison of the *duration* and *pattern* effects is depicted in Figure 9.

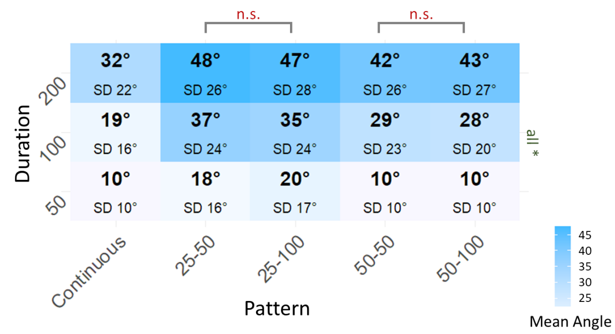


Figure 9. Angle changes for different *durations* and *patterns* while inflating the EA. If not indicated with *n.s.*, all conditions have significant differences.

Qualitative Results

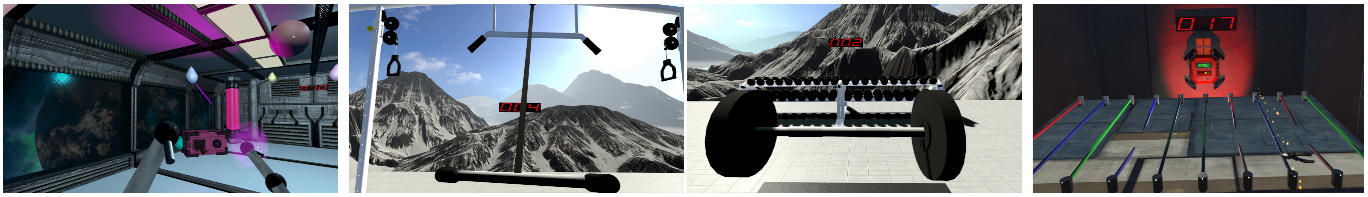
In general, users were inquisitive and interested in our system and appreciated the idea (P2, P5, P7, P14). It was also described as easy to understand (P1).

Comparing the *patterns*, most users preferred a *continuous* inflation because it "*felt more natural*" (P3, P10). Two users even mentioned that inflation intervals make them feel like a robot (P1, P7). However, this was not described as a necessarily negative comment, and the participants suggested to use it for simulating artificial movements. Interestingly, P17 and P18 commended the intervals as an intuitive way to bend their arm to a target position, because "*it tells to continue the motion rather than just pushing me in a direction*" (P17).

The comfort was described as pleasant or as not disruptive by almost every participant. P2 even described the extension actuator "*feels like a soft bicep massage*". Another participant found the feeling of the CA "*funny and cool*" (P18). However, not everyone would use it in its current state. For example, P10 and P12 thought the CA was not feeling very comfortable and applies too much pressure on the triceps. Also, particularly large participants found the jacket to be too tight (P4, P11) which was unavoidable with the prototype. Some participants (P1, P19) felt the EA is not applying enough pressure which we could observe especially for persons who told us they are doing many sports.

Lessons Learned and Discussion

As our results indicate, *PneumAct* actively engages kinesthetic motion through a pneumatic actuation of the users' arms. Here, different inflation durations and intervals resulted in significantly different angles of the users' arm. From our results, we could identify that different pause intervals have only a minor impact on the resulting angle if the inflation duration is the same (e.g., 50-50 and 50-100). However, there are significant differences between a continuous inflation and interval inflations for



a) Robots in Space b) Weight Lifting Exergame c) Wire Cutting Game

Figure 10. Screenshots of our three example applications: a) Robots, b) Weight Lifting Exergame, and c) Wire Cutting.

both, the CA and EA. With regards to the total duration of the CA, we could identify that there is a significant difference between a short (100ms), intermediate (200ms), and long (300ms) duration, however, there was only a minor non-significant change between 300ms and 400ms. Similar, the EA showed significant actuation intensities of the angle between short (50ms), intermediate (100ms), and long (200ms) total inflation durations. These findings allow us to design applications on different stimulation and feedback depending on the use case where we can decide how strong we want to actuate the user. For example, a short inflation resulting in a low angle could be used as notification, while a strong continuous inflation could be used as error feedback and prevent users' from reaching hazardous objects in critical situations. Further, users suggested using different patterns for specific purposes, such as using intervals for simulating a robotic motion feeling.

EXAMPLE APPLICATIONS AND TASKS

We designed three example games and applications in VR, based on the findings of the first study. Our aim of those applications was to cover previously evaluated variations within different scenarios. Therefore, we use different types of haptic actuation intervals and durations to provide kinesthetic force feedback, motion, or simulating different weights. We implemented them in Unity and used the HTC Vive as VR device.

Robots and Balloons in Space

Our first game is located in a lost space station where the user is playing a robot as depicted in Figure 10 a). The robot's task is to pop balloons floating the station with its lasers. In this scenario, we can benefit from haptics in two cases. First, the robot's laser creates a recoil while shooting and, thus, a counterforce can be applied to the user's arms through different inflation intensities of the CA. Second, the user should feel like a robot with artificial joint movements. Here, we apply haptic disruptions through inflation intervals of the EA that make the user's arm movements less fluid, creating the impression of being robotized (similar to [32]).

Weight Lifting Exergame

We designed an exergame where a user has to do sports in a virtual gym. For this, we created two exercises with two opposed movements that have to be performed as depicted in Figure 10 b). Firstly, the user has to lift a weight by performing barbell curls (*pushing* counterforce through a continuous inflation of the EA). Secondly, the user has to perform a triceps exercise by pulling down the handle of a cable pull (*pulling* counterforce through a continuous inflation of the CA). Here, the actuators apply a force to the arm joints making it harder to either contract or extend the muscles. Further, we added three different difficulties through changing the inflation intensities of the CA and EA.

Further, we resembled the barbell's and cable pull handle's physical shape by mounting both VR game-controllers to the sides of a pole. One controller was used to track the pole, while the second counterbalanced the first controller's weight evenly. Also, the controllers were used for vibrating in two modes: during pulling exercises, they vibrate on downward arm movements, and on upward movements for the push exercise.

Wire Cutting Game

A third application is set in a small room where the user has to cut correct wires in time to avoid an explosion. The latter has a kinesthetic impact force towards the user's body that extends the arms if a wrong wire is cut or the time ran out. However, wrong wires are not communicated up front but are visually indicated by electrical sparks if the user touches them with virtual pliers as depicted in Figure 10 c).

If *PneumAct*is enabled, touching a wrong wire simulates an additional electrical static that flinches the user's arm through inflating the CA with a long duration in short burst intervals. In addition, the game-controller will vibrate if vibrotactile feedback is enabled. Once a user cuts a wrong wire or the time runs out, the EAs are continuously inflating and simulate an impact force. The game is won after all correct wires are cut into two parts. Then, the game presents a firework to the user which actuates the EA in intervals synchronized to the animation.

STUDY II: EVALUATING PNEUMACT IN VRE

We conducted a second user study based on the findings of the first study where we evaluated the performance of *PneumAct* compared to game-controller-based vibrotactile feedback and a non-haptic baseline. Therefore, we investigated the participants' immersion, their impression of realism, and their enjoyment while using different haptic actuations inside our three VR applications. During all conditions, the participants were invited to freely explore the VRE rather than focusing on time constraints.

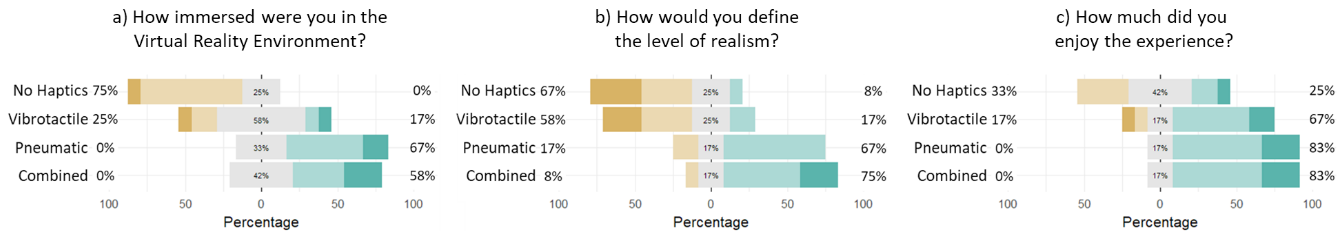


Figure 11. Participants' responses to our questionnaire during the second user study, asking for a) the immersion, b) the level of realism, and c) the overall enjoyment.

Study Design

We used a within-subject design where we wanted to explore how our system performs in real applications as presented in the previous example application section. We defined the type of haptic actuation as independent variable (IV) with four levels: 1) *no-haptics*, 2) *controller-based vibrotactile*, 3) *pneumatic*, and 4) *combined* pneumatic and vibrotactile haptics. As Dependent Variables we defined the level of enjoyment, realism and immersion, and asked the following questions:

1. How immersed were you in the Virtual Reality Environment experience?
2. How would you define the level of realism?
3. How much did you enjoy the experience?

We used a 5 point Likert scale ranging from *not at all* to *very much*. Here, the first question was directly asking about the immersion, while the other two questions asked for the realism and overall enjoyment based on the questionnaires of Lopes et al. [37]. We counterbalanced the order of the three applications and the different haptic actuation (no haptics, controller-based vibrotactile, pneumatic, combined) using a Balanced Latin square design. Each application had to be done using the four haptic conditions resulting in a total of $3 \times 4 = 12$ trials.

Procedure

After introducing *PneumAct* to the participants, we explained our three applications with their specific mechanics. Then, we explained the four conditions, and the HTC Vive if they were not familiar with it. We detailed the study's data protection policy and informed them about safety precautions which align with the guidelines of our ethic's committee. We then asked them to fill out a consent form and a demographic questionnaire including age, gender, and VR experience.

Once ready, we asked to wear the VR headset with the headphones on the ears to reduce background noises. Also, if participants had to perform the *pneumatic* or *combined* condition, we assisted with putting on the *PneumAct* jacket and made sure it is comfortable. Then, the participants could explore the VREs and were allowed to move around freely and repeat in-game tasks as often as they want. Once finished, we started the next application. Again, we did not force them to stop at any point as they could take their time as much as they wanted.

As soon as the participants completed all applications, we asked to fill out a final questionnaire rating the immersion, realism, and enjoyment on a 5 point Likert scale. After an optional break, we continued with the next feedback method and repeated the procedure until all conditions were conducted for each application. One study-session took about 60 minutes.

Participants

We recruited 12 participants (4 female) between 21 and 32 years (M=29, SD=3.5). Three of them never used VR while eight had tried it at least for a few times before. One user stated to be a regular VR user. Besides snacks and drinks, no compensation was provided.

Quantitative Results

We performed a non-parametric analysis of our Likert questionnaires' results and used Friedman's test to reveal significant effects. If tests indicated significance, we used Bonferroni-corrected Wilcoxon rank sum tests for pairwise post-hoc analysis. Because of the ordinal nature of the Likert data, we report the median $\tilde{x}$ of each result.

Immersion:

Our analysis indicated significant effects ($\chi^2(3) = 21.84$, $p < .001$) of the participants' immersion rating. Hereby, we observed the best immersion ratings for conditions using our jacket (cf. Figure 11 c)). We identified significant higher immersion ratings between *no-haptics* ($\tilde{x} = 2$) and *pneumatic* ($\tilde{x} = 4$, $p < .001$), as well as *combined* haptics ($\tilde{x} = 4$, $p < .001$). There were no significant effects between *pneumatic* and *combined* ($p > .05$), as well as for the *vibrotactile* ($\tilde{x} = 3$) conditions (all $p > .05$). The distribution is depicted in Figure 11 a).

Realism:

The analysis indicated significant effects for the level of realism ($\chi^2(3) = 22.45$, $p < 0.001$). Our post-hoc tests revealed that there is a significant higher level of realism between *pneumatic* ($\tilde{x} = 4$) and *no-haptic* ($\tilde{x} = 2$) actuation ($p < .05$), as well as between *combined* ($\tilde{x} = 4$) and *no-haptic* actuation ($p < .01$). While *vibrotactile* was rated similar compared to *no-haptic* (both $\tilde{x} = 2$), there were only significant effects compared to *combined* feedback ($p < .05$). The realism feedback is depicted in Figure 11 b).

Enjoyment:
Friedman's test indicated significant effects for the participants' enjoyment rating ($\chi^2(3) = 9.80$, $p < .05$). Pairwise comparisons revealed a significant higher enjoyment while using our *PneumAct* jacket (*pneumatics:* $\tilde{x} = 4$) compared to *no-haptics* ($\tilde{x} = 2$, $p < .05$). As depicted in Figure 11 c), this was also true between *no-haptics* and *combined* haptics ($\tilde{x} = 4$, $p < .05$). However, there were no significant effects between *vibrotactile* ($\tilde{x} = 4$) and *no-haptic* nor *pneumatic* actuation (both $p > .05$).

Qualitative Results
We collected qualitative feedback throughout the study, within the questionnaires, and during semi-structured interviews. We asked what they liked and disliked with regards to the different haptic actuations. Overall, all participants were very enthusiastic about the pneumatic actuation. They enjoyed the active forces (P10, P12) and described it as "*interesting concept*" (P6). Especially the CA was well received (P10, P11, P12) and participants described them as practical addition with a stronger force than they had imagined (P5, P6).

During the wire cutting game, participants liked the idea of "*getting actively warned before cutting a wrong wire*" (P7), and that it "*almost felt realistic as if the wires are powered*" (P8) while wearing the *PneumAct* jacket. The direct feedback while touching the wires made the game easier (P6, P9, P12), especially compared with *no-haptics* (P2, P12). Some participants also highlighted the "*effect of surprise at the moment of explosion*" while the *pneumatic* actuation confronted them with a direct force (P2, P3). One participant complained that it now "*does all the work [for me]*" (P11).

The robot game was perceived as fun and shooting lasers with both, *pneumatic* and *vibrotactile* feedback, was well received (P5, P9). One participant, however, described the robot-like inflations while moving as "*annoying*" (P11). In contrast, the exergame had mixed receptions. While multiple users thought *pneumatic* feedback gave a "*good impression of counterforce*" (P1, P2, P5, P11), some described the weight as "*too artificial*" (P4, P6) or "*not heavy enough while doing the exercises*" (P7).

Comparing *PneumAct* with *vibrotactile* haptics, most preferred either the *pneumatic* or *combined* actuation (P7, P9, P11). Using only vibration, they missed on-body haptics (P3), or the challenge during the exergame (P12). However, one participant stated that for "*playing the exergame, the pneumatic actuation was very intense and useful, while for playing the other games, vibration seemed sufficient*" (P6). One user appreciated the "*synchronous interaction between games and jacket*" (P4), while two wanted the *pneumatic* feedback applied faster (P2, P7). Concluding, most participants valued the positive effects, and, backed by the quantitative results, it works well along with additional game-controller-based *vibrotactile* feedback.

DISCUSSION AND LIMITATIONS
The results of our user studies show that our *PneumAct* system is a viable haptic addition in Virtual Reality Environments. In a first user study, we showed how different inflation durations and patterns significantly affect the angle of the arm. This allows us to apply our actuators in different scenarios and to influence the force and type of kinesthetic feedback as needed. For example, a continuous inflation triggered the most fluid movements, while intervals with short pauses were better for direct targeting of angles. However, *patterns* with short intervals resulted in significantly larger angles throughout all conditions. Some users also described the interval inflation as more artificial. However, they also suggested simulating restricted motion or the feeling of being something else, e.g., a robot.

In a second study, we showed that *pneumatic* kinesthetic actuation helps to significantly increase immersion in VR applications compared to *no-haptics* and *controller-based* vibrotactile feedback. Almost every user was convinced by our system and found the active actuation to be a practical solution to increase their enjoyment while playing. Further indicated through the questionnaires, our system consistently received better user ratings with regards to realism, enjoyment, and immersion, compared to plain vibrotactile haptics. We further could identify a positive effect when combining *PneumAct* with vibrotactile feedback, which is also a promising direction for conducting future work.

It has to be mentioned that our *PneumAct* approach comes with a few limitations. In our study, we only evaluated the effects on arm joints and have not investigated other promising body joints, such as the legs or back. We want to emphasize that actuating other body joints might yield different results.

Another limitation is that the EA is currently not optimized for different body sizes. While we could adjust the CA's length through shoulder straps, especially for smaller participants, we had to use additional Velcro straps to prevent the EA from slipping.

CONCLUSION
In this paper, we presented *PneumAct*: a haptic jacket embedding two types of actuators to contract and extend body joints for kinesthetic motion. We also contribute with a technical evaluation investigating the effects of different inflation *durations* and *patterns*, and a second user study comparing our system to controller-based and non-haptic feedback in three VR applications. As future work, we want to address the known limitations, and compare our concepts to feedback methods, such as EMS and vibrotactile suits. Also, we plan to investigate other use-cases, such as posture-correction or error-feedback.

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