Virtual Muscle Force: Communicating Kinesthetic Forces Through Pseudo-Haptic Feedback and Muscle Input

Michael Rietzler
Ulm University
Ulm, Germany
michael.rietzler@uni-ulm.de

Gabriel Haas
Ulm University
Ulm, Germany
gabriel.haas@uni-ulm.de

Thomas Dreja
Ulm University
Ulm, Germany
thomas.dreja@uni-ulm.de

Florian Geiselhart
Ulm University
Ulm, Germany
florian.geiselhart@uni-ulm.de

Enrico Rukzio
Ulm University
Ulm, Germany
enrico.rukzio@uni-ulm.de

Figure 1. We propose to enrich pseudo-haptic feedback with the additional input of muscle tension.

ABSTRACT

Natural haptic feedback in virtual reality (VR) is complex and challenging, due to the intricacy of necessary stimuli and respective hardware. Pseudo-haptic feedback aims at providing haptic feedback without providing actual haptic stimuli but by using other sensory channels (e.g. visual cues) for feedback. We combine such an approach with the additional input modality of muscle activity that is mapped to a virtual force to influence the interaction flow.

In comparison to existing approaches as well as to no kinesthetic feedback at all the presented solution significantly increased immersion, enjoyment as well as the perceived quality of kinesthetic feedback.

UIST'19, October 20-23, 2019, New Orleans, LA, USA

ISBN 978-1-4503-6816-2/19/10…$15.00
DOI: 10.1145/3332165.3347871

CCS Concepts

•**Human-centered computing** → *Virtual reality; Haptic devices;*

Author Keywords

Virtual reality; pseudo-haptic feedback; muscle input; evaluation

INTRODUCTION

Virtual reality (VR) as a consumer accessible tool is a rapidly evolving technology. It offers a high level of presence and immersion for users even though consumer hardware provides only visual and auditive stimuli. Haptic features are also available in the form of vibration but do only play a minor role in VR hard- and software. While interaction inside the virtual environment has become much more natural by using dedicated controllers tracked in three-dimensional space, it is still limited to pressing buttons as input modality and vibration as output modality.

Multi-sensory feedback has shown to enhance the feeling of presence [8], but usually the inclusion of an additional stimulus requires a whole new set of additional hardware. Real kinesthetic feedback for instance, is hard or impossible to implement without the help of a real world counterpart that is able to restrict user's motion. Hardware-based solutions range from the use of tethered objects [32] to exoskeletons [3] or dedicated robots [31].

Current VR devices, however, usually consist only of the HMD and two controllers that are tracked in 3D space to interact with virtual objects. Building on such hardware, a completely different approach is pseudo-haptic feedback, that aims at delivering the illusion of haptic features solely by an altered visual feedback [38, 41]. The downside of hardware-based solutions, that pseudo-haptic feedback is not affected with, is a limited resolution and especially size and complexity of the systems. Fully natural kinesthetic feedback always requires a grounded counterpart in the real world. Pseudo-kinesthetic feedback – though different levels of kinesthetic forces can be displayed without additional hardware – is more or less a metaphor of forces that otherwise could not be displayed with available systems. Since such approaches only consider the feedback side of the interaction flow, one implication of such metaphorical feedback is that it does not involve the user's muscles for the interaction. Independent of the strength of kinesthetic forces, the user does not necessarily have to exert.

While prior works on pseudo-haptics concentrate on the output, this paper extends this concept to an input component that is embedded in the entire interaction flow. As long as only the output is considered, the user may lose some control over his actions. We propose to combine pseudo-haptic feedback with the additional input modality of muscle tension. By additionally using muscles as input devices it is possible to realize both input and output of haptic interaction without a physical counterpart and hand back control to the user. Pseudo-haptic feedback weakens the bond between tracked controller and virtual hand representation. By reaching through or into a virtual object the hand representation is blocked by the object and an offset to the controller's position results. It was proposed to use the offset between tracked controller and the virtual representation of the hand as a force [40]. This way, a virtual object (even if there is no physical reference) can resist the user (or at least their visual representation) and the kinesthetic feedback results in a visual offset depending on the virtual physical properties of an object. Though such an approach also affects the interaction, since a user has to stretch further to move heavier objects, it does not necessarily involve a real tensing of the user's muscles. We suggest to add a supplementary virtual force into the pseudo-haptic interaction cycle that is dependent on the measured tension of action related muscles. While pseudo-haptic tracking offsets can be used to visually communicate the forces, the measured muscle activity can be used as a countering force to these offsets. A higher weight can thus be communicated via an increasing offset, which decreases as the user begins to exert himself. In this way we want to communicate pseudo-haptic forces more clear and provide users greater control over their actions.

The advantage of the presented approach is, compared to already introduced solutions which used muscle contractions as input, the latter no longer has to be realized as a hard threshold. Previous works have designed muscle input in such a way that a certain threshold must be reached, e.g. to lift a virtual object. In this case there is a hard threshold from which an object can be lifted and held. If the measured values fall below this threshold, the object is dropped or cannot be moved. This hard threshold is no longer needed in our presented approach, since the measurement of muscle contractions can be integrated as an additional force inside the VR application. A weak muscle contraction therefore leads to a high tracking offset, but does not prevent virtual objects from being lifted or moved.

In a user study we found that such an approach can significantly improve immersion as well as enjoyment in VR applications. The use of muscle tension as additional input channel further increased the illusion of kinesthetic feedback as well as the perceived realism of the VR experience we implemented.

The main contributions of this work are:

- The concept of enriching pseudo-haptic feedback with an additional input modality and a concrete implementation using muscle exertion as input and visual manipulations as feedback channel
- A study showing increased enjoyment and immersion, as well as an increased level of the perceived quality of haptic feedback using such an implementation.

RELATED WORK

Multi-sensory feedback in general [8, 12] – and haptics being one of them – plays a major role for the feeling of presence in VR. Humans can differentiate various object properties like texture, hardness, temperature and weight by our haptic senses [26].

Hardware solutions

Our work concentrates on kinesthetic feedback, which is used to display directional forces. One way to achieve this goal is to make use of handheld [32] or stationary mounted tethers around the user [17]. More complex is the use of exoskeletons on the hands [3, 4, 10, 14] or on the arms of users [34]. Exoskeletons can also be attached between two body parts [49].

Passive-Haptic Feedback

The virtual and physical world are differing, but this mismatch can be compensated. There are several approaches to partially recreate the virtual world inside the real one. Robots [13, 31, 50] or other humans [7] can be used as helpers or actuators. There are also approaches on passive haptic feedback using props as physical counterpart for the virtual ones [16, 21, 46]. The mapping of real world objects to virtual objects can also be supported by slightly manipulating the user's motion to match surfaces [20, 45] or objects [2].

Pseudo-Haptic Feedback

Beside dedicated hardware and passive-haptic feedback there is a third strategy for the communication of kinesthetic feedback: Pseudo-haptics. The basic concept is to circumvent the real stimulus by another stimulus (most of all using vision). This way, object properties can be *faked* by synchronously presenting visual stimuli to support the performed interaction.

Various properties like friction [23, 24], stiffness [47] or tactile feedback [37] can be displayed without the need for a real world counterpart. There are also works on simulating directional forces [25, 22] on external displays or the subtle resistance of airflow [38, 39] in VR. The aim of all these approaches is to slightly manipulate the virtual representation of the hands without being recognized by the user. Unlike the naive vision of perfect illusion, such manipulations may also be applied with the user being aware of being manipulated and therefore breaking with proprioception. Though not relying on forces, it was suggested to support the feeling of slow-motion in VR by visually slowing down user motions [42]. In their proposed solution, depending on the user's velocity, there was an obvious difference between proprioception and the visual feedback.

Such obvious dissent between proprioception and visual feedback was also used to communicate kinesthetic feedback. This way even virtually heavy objects could provide respective feedback when being lifted [41]. Samad et al. [43] further explored the range of the control/display-ratio to simulate weight in virtual reality. A similar approach was presented for kinesthetic feedback in general [40] where also a multi-sensory pseudo-haptic feedback approach, which combines visual and vibration feedback, was presented.

Our approach and implementation is built on these presented works and the concept of pseudo-haptic feedback with perceivable offsets in general.

Muscles as input or output devices

Muscles have already been used for input and output for interaction. Electrical muscle stimulation (EMS) was used as feedback channel [11, 28, 29, 35, 48]. Lopes et al. used this approach to provide ungrounded kinesthetic feedback by actuating opposing muscles [30]. They actuate an opposing muscle to force the user to tense the desired one . Our approach has some similarities but while our proposed interaction also relies on exerting the user, we do not force the user to tense their muscles by electrically stimulating the opposing muscle. In our approach, the user is encouraged to tense a muscle to support the intended interaction.

Nacke et al. [33] investigate the effects of using physiologically controlled games. They argue, that respective sensors have to be mapped intuitively and matching to the desired action for direct interaction. Electromyography (EMG) was used for other interaction techniques such as e.g. pointing and clicking [15], same-side hand interactions [18] or hand gestures (e.g. [9, 19, 52, 51]), however often using algorithmic or learning-based solutions to derive other biomechanical parameters like hand pose from muscular activity before.

Ponto et al. used biofeedback to interact with virtual objects with a certain mass [36, 6]. In their system, users require to exert a calibrated amount of exertion to grasp and hold objects.

Hirooki Aoki [1] examined effects of pseudo-haptics on muscle activity to support exercising. He found that such approaches can indeed increase the amount of measured muscle activity.

COMBINING PSEUDO-HAPTICS WITH MUSCLE INPUT

Prior works that utilized exertion for interaction in VR implemented their approach in a way, that a certain threshold of force was required to lift and hold virtual objects. Pseudo-haptics, on the other hand, was implemented as discrete and barely noticeable feedback as well as by treating it as some kind of metaphor for kinesthetic forces using perceptible tracking offsets. We propose to include muscle activity as additional input for pseudo-haptic feedback to let virtual forces influence the whole interaction cycle. While prior approaches always require a minimum amount of force to keep the object grabbed, we utilize pseudo-haptics as additional feedback. In this case, offsets are used to indicate the weight of an object. As the user exerts, the amount of offset will be reduced according to the force a user applies.

Humans are able to tense their two opposing muscles, even without applying forces to physical objects. This allows the user to actually influence the applied strength of forces in the VE using the same medium as in the real world, which is the tension of muscles.

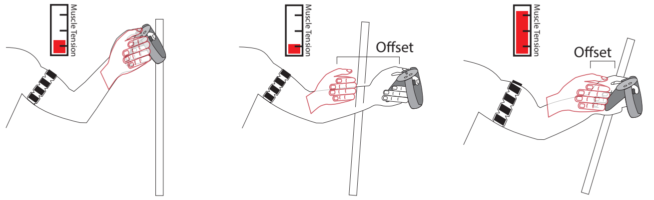

Figure 2. The offset between real hand and virtual hand representation, which is used for passive-haptic feedback, is dependent on muscle tension. When the user flexes his biceps, he is able to reduce the offset and therefore, apply higher forces in the virtual world.

The basic idea of pseudo-haptic feedback is to simulate kinesthetic forces by offsets between real limbs and their virtual representation. For greater expressiveness, this offsets can reach magnitudes where they become perceptible to users [41]. Depending on the movement the user performs and the resistance of the virtual object, the offsets vary in size. By combining pseudo-haptic feedback and muscle tension as input, this offset can additionally be influenced by the tension the user creates. The more a user flexes their muscles, the greater the applied force in the VE. Therefore, the offset is scaled by the physiologically created muscle tension.

IMPLEMENTATION

Our implementation consists of two separate virtual forces that are applied when a user interacts with, pushes or pulls an object. One is the *offset force* which was implemented as proposed by prior work [41, 40]. In this approach the the visual representation of the controller in the form of virtual hands are decoupled from the actual tracked position of the controller and are therefore treated as ordinary objects by the physics engine. The virtual hands are always pulled by an attraction force towards the position of the tracked controllers. With no further restrictions, the virtual hand representation is in the exact the same position as the corresponding controller in the real world. As soon as the real hands reach behind or inside a virtual object, the virtual hands collide with this object. As a result, the virtual hands apply their attraction force to the virtual object and may manipulate it, dependent on physical properties. The force that is applied to the virtual object depends on the size of the offset between virtual hand and tracked controller. Therefore, heavier objects with a higher inertia and friction require a larger offset to be manipulated. If the offset reaches a specified threshold (e.g. in case of a static object), clipping is used as escape strategy.

The *muscle force* is the second virtual force we included as a novel addition over previous works. The direction of the *muscle force* acts in the same direction as the *offset force* and its magnitude dependents on the measured muscle tension. As long as the user does not flex his muscles, only the offset force is effective. As soon as the muscles are tensed (and depending on the measured intensity) the offset force acts as support (see figure 2). This allows e.g. a heavier object to be lifted with a lower offset as long as the muscles are flexed.

Since the offset force was already described in prior works [41, 40], we will not discuss the respective implementation and only discuss the implementation of the muscle force in the following.

The Muscle Force

We used the Thalmic Myo armband to measure muscle tension. The armband consists of eight EMG sensors and is connected to a computer via bluetooth. In our implementation, we did not aim at distinguishing between different muscles (e.g. biceps and triceps to separate pushing from pulling) since when tensing muscles without real world counterpart, two opposing muscles must be tensed to keep the posture. Therefore, pushing a virtual object results in the tension of biceps and triceps as well.

Since the hardware we used possesses eight EMG sensors, our implementation takes all EMG signals into account, but only the largest factor is considered for further calculations. In this way, the Myo wristband itself does not need to be calibrated and can be attached in any rotation. Our approach could also be implemented with a single EMG sensor on one of the muscles.

Since the measured EMG signal is very noisy, an OneEuroFilter [5] is applied to smooth the measures before any further calculations.

Calibration: Since the minimum and maximum of the measured EMG signal strongly varies between users, a calibration of strength is inevitable to utilize muscle tension as input device. We perform a two point calibration. The user is first asked to relax their upper arm for 2 seconds. During this time frame, data is collected from the EMG sensors and a mean is calculated after excluding outliers. This procedure is then repeated with a flexed muscle for the maximum value.

Normalization: We then normalize the measured EMG values based on the calibrated maximum and minimum by subtracting the minimum from the current measure and dividing it by the maximum. We further restrict the range to values between 0 and 1.

Conversion to force: Based on the normalized measures a force is applied inside the VR application as long as the user interacts with an object. In our implementation, the conversion from the normalized EMG signal to a force was done in a linear way, multiplying the normalized EMG signal by 110N. This value was chosen according to [44] as the force a human can apply standing with her primary arm and shoulder muscles. The resulting scalar is then multiplied by the normalized direction vector between tracked controller and virtual hands (the direction of the offset) and applied as additional force.

The muscle force ($F(m)$) is therefore calculated using the current measurement (m), the minimum (min) and maximum (max) of the calibration and the direction of the offset ($\hat{O}$) as follows:

$$F(m) = \frac{m - min}{max} \cdot 110N \cdot \hat{O} \tag{1}$$

If a more realistic application is desired, we suggest to measure and use this maximum force for each user to let the application react on each individual according to his or her real strength. Furthermore, different operations, such as pushing, lifting and pulling, could be distinguished and treated differently. It is also possible to substitute the proposed linear interpolation by a more complex one. One suggestion is to use several calibration objects that are lifted by the user while measuring their muscle activity. Depending on the number of calibration objects a more or less reliable curve could be fitted to replace the linear function.

STUDY

To evaluate the proposed approach against state-of-the-art pseudo-haptic feedback approaches and a system without kinesthetic feedback (as used in most common VR applications) we designed a VE in which a user is asked to directly manipulate objects to progress and reach other locations inside the environment. We used an Oculus CV1 as HMD and two Touch controllers for the input.

Participants

For our study we recruited 21 participants (5 female) aged between 22 and 29 years with a mean of 25 (SD: 2.7). Most of them were students or employees of our university since we recruited on campus. We asked the participants to state how many months of experience they have with VR devices. The responses varied between 0 and 36 months ago with a mean of 6 month ago (SD: 9 months).

Method

We designed our study as a within-subject design having three conditions: no pseudo-haptics (*none*), pseudo-haptic feedback only (*PH*) which was implemented similarly to [40] and pseudo-haptic feedback with muscle force (*PHM*) that used the same implementation for the offset force as the *PH* condition but also the described implementation of the muscle force in addition. The differences and effects on the test applications are discussed in more detail in the *Study Application* section. All conditions were presented in a counter balanced order using a latin square.

We compared the three conditions in regard to immersion and enjoyment which were both assessed by the E^{2}I questionnaire

[27]. Additionally, we used five single item questions to get insights on the perceived quality of the haptic feedback as proposed by prior work [40]. We asked the participants to state how much they agree with the following statements on a scale from 1 (=strongly disagree) to 6 (=strongly agree): *"I could feel a resistance"*, *"The representation of physical constraints felt realistic"*, *I had the feeling of manipulating real objects* and *"I could influence the behavior of objects with my actions"*.

To get further insights on the personal preferences of each implementation we also included the item: *"I liked this representation of physical constraints"*.

Study Application

Our test application was a virtual environment in which participants had to interact directly with virtual objects. The participants were automatically teleported to the next task, after they completed the prior one. Since one of the study's goal was to find out whether the respective interaction techniques felt natural and fit the visual impressions of virtual objects we decided to implement a visually rich virtual environment. The visual appearance of objects the participants interacted with should have a realistic character to create expectations about their behaviour and physical properties.

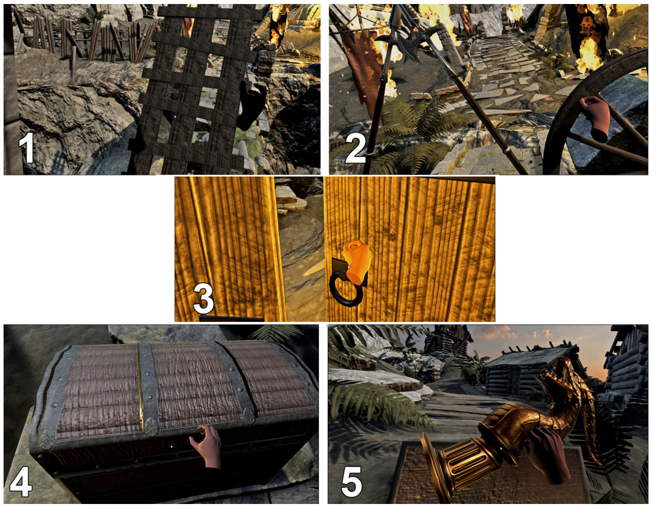

Figure 3. The five different interaction tasks that were implemented for this evaluation. Participants were asked to push [1,3], turn [2] and lift [4,5] objects while applying varying amounts of force for each of them.

Tasks: We chose tasks that do not necessarily require kinesthetic feedback but could benefit from it. Depending on the condition, the behavior of these objects varied as soon as they were touched. The differences will be discussed in more detail in the *Conditions* paragraph.

The first task to accomplish was to push a wooden structure, so that it tips over and falls into a small chasm where it completes a bridge in front. The wooden structure was defined lightweight and was easy to move in all conditions.

After the completion of the first task, participants were automatically teleported to the second location at the end of the provisional bridge just created. Here, they needed to unblock the path by cranking a wheel that slides the barrier (two spears) out of the way. Since the wheel had to be pulled towards the user, this task demanded the opposite direction of motion as task one. As the gate opened up, the user was again teleported – this time to a wooden double-winged door which was already in user's line of sight. As a third task, the participants needed to open both wings of this door. This required, much like the first task, a push operation. The difference was, that the doors were designed to possess a much higher resistance compared to the wooden structure in task one. This difference though, could only be observed in the two pseudo-haptics conditions (*PH* and *PHM*) since the respective forces cannot be displayed without (similar to current state-of-the-art VR games). Once both wings are wide open, the user was teleported to the last location.

Here, the user faced a large wooden chest. First, the heavy lid had to be lifted beyond the point, where gravity takes over and the lid falls back. The second part was to grab and lift a golden dragon statue which was placed inside the chest. When compared to the lid of the chest, this statue is designed more lightweight. The last two tasks therefore consisted of two different lifting operations, one heavy and one lightweight.

By getting to the golden dragon statue, the user has achieved his quest and the experience was over.

Conditions: Depending on the condition, the interaction with objects slightly differed, since the *PH* as well as the *PHM* condition introduced different challenges (reach further due to the offset force and additionally tense the muscles to move an object). The impact of these differences were then assessed and compared using the described questionnaires. The following paragraphs summarize the differences.

The **none** condition is the state-of-the art of most VR applications and did not provide any kinesthetic feedback at all. The task of moving virtual objects could be solved without any additional challenge, since the objects and the virtual hands moved as the real hands of the users did, by following the tracked controllers without any manipulation.

The **PH** condition relied on already proposed implementations of pseudo-haptic feedback ([40, 41]). To solve their tasks, the participants had to put more effort into moving the objects, since the force applied to a virtual object dependent on the offset between tracked controller and the virtual hands. Depending on the weight of an object, the user had to reach farther to move it.

The **PHM** condition used the same implementation as the *PH* condition but made use of the described *muscle force*. Depending on the measured tension of the user's muscles, an additional force was applied to the virtual object. This resulted in potentially less offset and more exertion compared to the *PH* condition.

Independent from condition the maximum offset didn't exceed 42 cm as proposed by Rietzler et al. [41]. In this case, clipping was used as escape strategy.

Procedure

The participants were welcomed and introduced to the topic of the study. We only communicated that the study was on interacting with virtual objects. None of them was further informed about the details of the underlying implementations but informed about what they had to do to move heavier objects (e.g. exert their muscles or reach farther). Each participant then completed a demographic questionnaire and signed a consent form.

Before any condition started, participants were introduced to the five tasks and what they needed to do to accomplish the task. Ahead of the actual experience, participants found themselves in a virtual training environment, where they could interact with a sample object to try out and get used to the current condition. In case of the *PHM* condition we calibrated the EMG sensors before starting the training. After completing the experience with one condition, participants were asked to fill the questionnaires described in the *Method* section.

After completion, this procedure was repeated for the remaining conditions in a counterbalanced order.

Results

We compared each of the scores and items described in the *Method* section using Friedman's variance analysis. If a significant difference was present, we used Wilcoxon's signed rank test to make pairwise comparisons. All stated significances were adjusted by the Bonferroni correction. Boxplots of all values are shown in figure 4. Significant values below 1% are referred to as highly significant and values below 5% are referred to as significant in the following.

Immersion differed highly significantly (p <.01) within the three conditions. Pairwise comparisons showed a significant difference between *none* and *PHM* (p <.01; r = .28) and between *PH* and *PHM* (p <.05; r = .16).
Enjoyment scores differed highly significantly. We found the differences between *none* and *PHM* (p <.01; r = .30) and between *PH* and *PHM* (p <.01; r = .22).
Realism ratings revealed significant differences between *none* and *PHM* (p <.01; r = .26) and between *PH* and *PHM* (p <.05; r = .16). While the feeling of **touching real objects** highly significantly differed between all conditions: *none* vs. *PH* (p <.01; r = .19), *none* vs. *PHM* (p <.01; r = .33) and *PH* vs. *PHM* (p <.01; r = .14).
The **feeling of resistance** also differed highly significantly between all conditions. The strongest effect sizes were found between *none* and *PHM* (p <.01; r = .38), and between *none* and *PH* (p <.01; r = .21). The *PHM* condition provided a significantly stronger feeling of resistance then the *PH* condition (p <.05; r = .17).

The feeling of being able to **influence objects** was highly significantly stronger in the *PHM* condition compared to *none* (p <.01; r = .28). Though not differing significantly, we found small effect sizes comparing *none* and *PH* (p >.05; r = .14) as well as *PH* and *PHM* (p >.05; r = .14).

Though we found a significant difference comparing all conditions regarding the results of the single item questions whether the participants agree to **like** the presented approach, we did not find any significant differences when comparing pairwise.

Discussion

Immersion: Though the boxplots as shown in 4 do not indicate strong variations between conditions, the results support the assumption that the inclusion of muscle tension as an additional input for pseudo-haptics can increase immersion.

The **enjoyment** scores were very high for each condition, though there is a clear tendency towards the *PHM* condition resulting in a higher enjoyment. Interestingly, the variances of the scores differed most in the *PHM* condition. While most of the participants had most fun with the proposed approach, few did like it less. In informal discussions after the study was finalized, some participants stated that they just wanted to complete the challenge. They saw the pseudo-haptics as some kind of disturbance, that limited them to complete the challenge as fast as they could do without such modifications. We could not observe similar ratings considering immersion. We assume that the additional input was more compelling for almost every participant, while some saw themselves constrained in managing the tasks. However, this additional challenge was not perceived as negative by every participant. The majority stated that they felt more involved in the virtual world because of the possibility to influence the objects with their own muscle power. Due to the additional challenge, some participants stated that they were more pleased with the success.

Perceived haptic quality and realism: The item that was influenced most by pseudo-haptics in general was the feeling of *resistance*. While the respective scores are obviously quite low without additional feedback (median: 2 out of 6), participants rated it much higher with the proposed combination of pseudo-haptic feedback and muscle input (median: 5). The approach also strongly influenced the feeling of interacting with *real objects* (median 3 vs. 5) and the overall realism of the application. Interestingly, the ratings whether participants *liked* the presented approach did not vary strongly, though all other ratings were improved by pseudo-haptics, including enjoyment. This could be due to differences in characteristics of the conditions. In the *none* and *PH* condition, the users might feel that they have a super power to move every object without having any fatigue or resistance from objects. As soon as the muscles get involved, this is no longer the case. The user must tense his muscles, which may make the interaction more realistic and intense, but also more strenuous and difficult. As mentioned before, there were some participants who liked the additional challenge, while others, who were most of all into completing the challenge stated that it would make the virtual experience more intricate. We assume, that if these participants only knew a single version of the experience, the ratings would differ more strongly.

Limitations

We did not compare our approach to hardware-based solutions which provide physical kinesthetic feedback. As the boxplots in figure 4 show, we achieved very high ratings in *feeling of resistance* and *feeling of touching real objects* with our proposed approach. However, the absolute scores of these results should be interpreted with care. We assume that the rating would be much lower when comparing a pseudo-haptic approach with real physical stimuli.

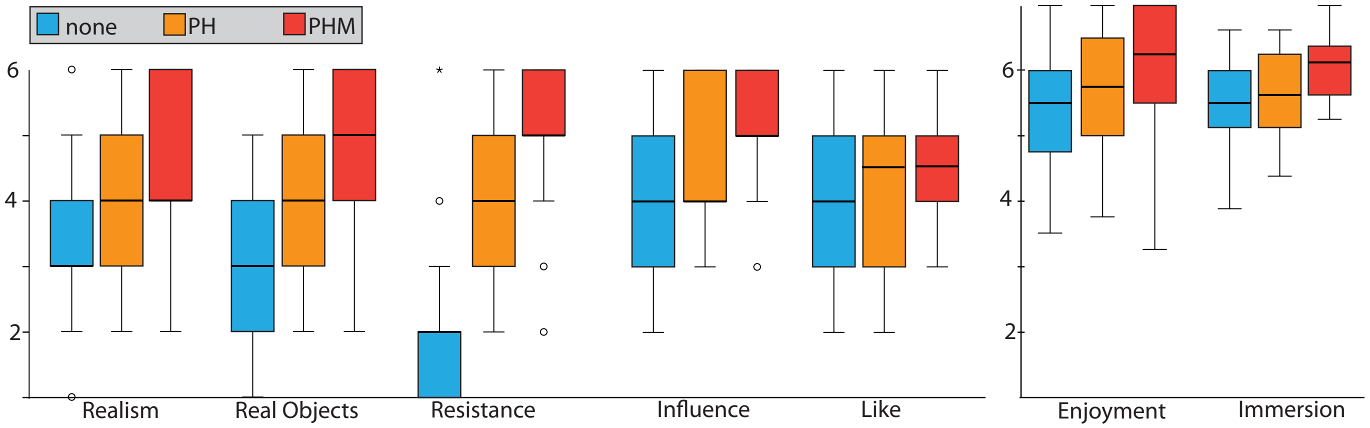

Figure 4. Left: Boxplots of the answers of our single items as described in the *Method* section. Right: Boxplots of the E^{2}I enjoyment and immersion scores.

The enjoyment scores are little difficult to interpret. While the scores were higher in both pseudo-haptics conditions, there were also some low ratings (see the boxplot's whiskers). Considering the informal verbal feedback which we collected by talking to the participants after the study, the pseudo-haptic feedback as well as the proposed muscle input was perceived ambivalent. While most of the participants liked and enjoyed such feedback, others saw themselves restricted in their actions. When playing without the pseudo-haptic feedback or muscle input, every task could be solved much faster, since there was actually no challenge at all. We therefore assume, that the respective ratings were very much influenced by the basic attitude of the participants: if they just wanted to complete or whether they wanted to be challenged.

IMPLICATIONS

Using muscle tension as input has shown to be a promising way to enhance pseudo-haptic feedback. Most of the participants liked the approach and valued their additional influence on manipulating the virtual environment. Based on the feedback we got from the participants as well as by our own experience during implementing and testing we suggest to consider the following when designing applications with pseudo-haptic feedback with muscle input:

Familiarization is a very important factor. Some participants had no problem in tensing their muscles without a real world counterpart, while others needed some time to get used to it. We therefore suggest to include a tutorial, where users can try to interact with an object based on their own muscle tension.

Exhaustion is a factor that should be considered as well. Though there is no real object that is pushed, pulled or lifted, participants stated that it was indeed exhausting to interact with the virtual objects. We therefore suggest using the approach with care. Not every action a user performs in the virtual world should be based on strong muscle tension. Such high exertion levels may be used best to design additional challenges that make use of physical exhaustion, while lower levels (that could also be easily compensated by the pseudo-haptic feedback's offset force) can be used without limitations.

Challenges, though, have to be designed in an adequate way. In our tests, we found that some participants just wanted to finish as fast as possible. Compared to the alternative of having some kind of superpower (which was given in the *none* condition, where the user could manipulate objects without effort), some interpreted the additional challenge as limitation.

Applications can range from more realistic (like simulations) to unrealistic game effects. If the goal is high realism, the function which converts the measured values into virtual forces could be adapted to the individual and calibrated more fine-granularly. Real reference objects could also be included in this calibration step.

On the other hand, the approach is also suitable for displaying game effects. If a character becomes stronger, the virtual muscle strength could become stronger and less muscle tension would be required to lift heavier objects. If a character is weakened it could be scaled to be smaller. In the latter case, each action in the virtual world would be associated with more effort.

CONCLUSION

The ability to interact directly with virtual objects via controllers tracked in 3D space is becoming of great importance in VR applications. Though the ability of having a natural interaction, one with haptic stimulation, within such scenarios is still limited. Since it is very hard to develop hardware solutions that are suitable to communicate the broad range of possible kinesthetic feedback, we propose to enhance pseudo-haptic feedback with muscle activity as additional input. Neither pseudo-haptic feedback nor the measurement of muscle tension demand actual forces, and therefore neither haptic props nor complicated hardware are required. Our proposed approach uses priorly presented pseudo-haptic feedback techniques, where physical properties are communicated by offsetting the virtual hand from the tracked controllers. We propose to use the user's muscle tension as additional input to enhance respective interactions, make them more natural and give the user more control.

In a user study, we found that such an approach is suitable to enrich the interaction with virtual objects. We found a significant increase of immersion as well as enjoyment. Participants also rated the approach to be more realistic compared to no pseudo-haptics at all, as well as compared to pseudo-haptic feedback only. Additionally, we found an improvement of the feeling of physical resistance.

ACKNOWLEDGMENTS

This work was supported by the Emmy Noether research group "Mobile Interaction with Pervasive User Interfaces" funded by German Research Foundation (DFG).

REFERENCES

[1] H. Aoki. 2018. Muscle Activity Resulting from Pseudo-haptic Occurrences. In *2018 12th France-Japan and 10th Europe-Asia Congress on Mechatronics*. 304–307. DOI: `http://dx.doi.org/10.1109/MECATRONICS.2018.8495673`

[2] Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D Wilson. 2016. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1968–1979.

[3] Jonathan Blake and Hakan B Gurocak. 2009. Haptic glove with MR brakes for virtual reality. *IEEE/ASME Transactions On Mechatronics* 14, 5 (2009), 606–615.

[4] Mourad Bouzit, Grigore Burdea, George Popescu, and Rares Boian. 2002. The Rutgers Master II-new design force-feedback glove. *IEEE/ASME Transactions on mechatronics* 7, 2 (2002), 256–263.

[5] Géry Casiez, Nicolas Roussel, and Daniel Vogel. 2012. 1 filter: a simple speed-based low-pass filter for noisy input in interactive systems. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2527–2530.

[6] Karen B Chen, Kevin Ponto, Ross D Tredinnick, and Robert G Radwin. 2015. Virtual exertions: evoking the sense of exerting forces in virtual reality using gestures and muscle activity. *Human factors* 57, 4 (2015), 658–673.

[7] Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch. 2015. Turkdeck: Physical virtual reality based on people. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, 417–426.

[8] H. Q. Dinh, N. Walker, L. F. Hodges, Chang Song, and A. Kobayashi. 1999. Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments. In *Proceedings IEEE Virtual Reality (Cat. No. 99CB36316)*. 222–228. DOI: `http://dx.doi.org/10.1109/VR.1999.756955`

[9] Christian Eckhardt, John Sullivan, and Krzysztof Pietroszek. 2017. Flex: Hand Gesture Recognition Using Muscle Flexing Sensors. In *Proceedings of the 5th Symposium on Spatial User Interaction (SUI '17)*. ACM, New York, NY, USA, 164–164. DOI: `http://dx.doi.org/10.1145/3131277.3134360`

[10] Takahiro Endo, Haruhisa Kawasaki, Tetsuya Mouri, Yasuhiko Ishigure, Hisayuki Shimomura, Masato Matsumura, and Kazumi Koketsu. 2011. Five-fingered haptic interface robot: HIRO III. *IEEE Transactions on Haptics* 4, 1 (2011), 14–27.

[11] Farzam Farbiz, Zhou Hao Yu, Corey Manders, and Waqas Ahmad. 2007. An electrical muscle stimulation haptic feedback for mixed reality tennis game. In *ACM SIGGRAPH 2007 posters*. ACM, 140.

[12] Julia Fröhlich and Ipke Wachsmuth. 2013. The Visual, the Auditory and the Haptic – A User Study on Combining Modalities in Virtual Worlds. In *Virtual Augmented and Mixed Reality. Designing and Developing Augmented and Virtual Environments: 5th International Conference, VAMR 2013, Held as Part of HCI International 2013, Las Vegas, NV, USA, July 21-26, 2013, Proceedings, Part I*, Randall Shumaker (Ed.). Springer Berlin Heidelberg, Berlin, Heidelberg, 159–168. DOI: `http://dx.doi.org/10.1007/978-3-642-39405-8_19`

[13] Peter E Gruenbaum, William A McNeely, HA Sowizral, TL Overman, and BW Knutson. 1997. Implementation of dynamic robotic graphics for a virtual control panel. *Presence: Teleoperators and Virtual Environments* 6, 1 (1997), 118–126.

[14] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. 2016. Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1991–1995.

[15] Faizan Haque, Mathieu Nancel, and Daniel Vogel. 2015. Myopoint: Pointing and Clicking Using Forearm Mounted Electromyography and Inertial Motion Sensors. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 3653–3656. DOI: `http://dx.doi.org/10.1145/2702123.2702133`

[16] Hunter G Hoffman. 1998. Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments. In *Virtual Reality Annual International Symposium, 1998. Proceedings., IEEE 1998*. IEEE, 59–63.

[17] Seungzoo Jeong, Naoki Hashimoto, and Sato Makoto. 2004. A novel interaction system with force feedback between real-and virtual human: an entertainment system: virtual catch ball. In *Proceedings of the 2004 ACM SIGCHI International Conference on Advances in computer entertainment technology*. ACM, 61–66.

[18] Frederic Kerber, Pascal Lessel, and Antonio Krüger. 2015. Same-side Hand Interactions with Arm-placed Devices Using EMG. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '15)*. ACM, New York, NY, USA, 1367–1372. DOI: `http://dx.doi.org/10.1145/2702613.2732895`

[19] Jonghwa Kim, Stephan Mastnik, and Elisabeth André. 2008. EMG-based hand gesture recognition for realtime biosignal interfacing. In *Proceedings of the 13th international conference on Intelligent user interfaces*. ACM, 30–39.

[20] Luv Kohli. 2010. Redirected touching: Warping space to remap passive haptics. In *3D User Interfaces (3DUI), 2010 IEEE Symposium on*. IEEE, 129–130.

[21] Luv Kohli, Eric Burns, Dorian Miller, and Henry Fuchs. 2005. Combining passive haptics with redirected walking. In *Proceedings of the 2005 international conference on Augmented tele-existence*. ACM, 253–254.

[22] A. Lecuyer, J. M. Burkhardt, S. Coquillart, and P. Coiffet. 2001. "Boundary of illusion": an experiment of sensory integration with a pseudo-haptic system. In *Proceedings IEEE Virtual Reality 2001*. 115–122. DOI: `http://dx.doi.org/10.1109/VR.2001.913777`

[23] Anatole Lécuyer, Jean-Marie Burkhardt, and Laurent Etienne. 2004. Feeling Bumps and Holes Without a Haptic Interface: The Perception of Pseudo-haptic Textures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '04)*. ACM, New York, NY, USA, 239–246. DOI: `http://dx.doi.org/10.1145/985692.985723`

[24] Anatole Lécuyer, Jean-Marie Burkhardt, and Chee-Hian Tan. 2008. A Study of the Modification of the Speed and Size of the Cursor for Simulating Pseudo-haptic Bumps and Holes. *ACM Trans. Appl. Percept.* 5, 3, Article 14 (Sept. 2008), 21 pages. DOI: `http://dx.doi.org/10.1145/1402236.1402238`

[25] A. Lecuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet. 2000. Pseudo-haptic feedback: can isometric input devices simulate force feedback?. In *Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048)*. 83–90. DOI:`http://dx.doi.org/10.1109/VR.2000.840369`

[26] Susan J Lederman and Roberta L Klatzky. 1987. Hand movements: A window into haptic object recognition. *Cognitive Psychology* 19, 3 (1987), 342 – 368. DOI: `http://dx.doi.org/https://doi.org/10.1016/0010-0285(87)90008-9`

[27] JJ-W Lin, Henry Been-Lirn Duh, Donald E Parker, Habib Abi-Rached, and Thomas A Furness. 2002. Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In *Virtual Reality, 2002. Proceedings. IEEE*. IEEE, 164–171.

[28] Pedro Lopes and Patrick Baudisch. 2013. Muscle-propelled force feedback: bringing force feedback to mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2577–2580.

[29] Pedro Lopes, Alexandra Ion, and Patrick Baudisch. 2015. Impacto: Simulating physical impact by combining tactile stimulation with electrical muscle stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, 11–19.

[30] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 1471–1482.

[31] William A McNeely. 1993. Robotic graphics: A new approach to force feedback for virtual reality. In *Virtual Reality Annual International Symposium, 1993., 1993 IEEE*. IEEE, 336–341.

[32] Jun Murayama, Laroussi Bougrila, YanLin Luo, Katsuhito Akahane, Shoichi Hasegawa, Béat Hirsbrunner, and Makoto Sato. 2004. SPIDAR G&G: a two-handed haptic interface for bimanual VR interaction. In *Proceedings of EuroHaptics*, Vol. 2004. 138–146.

[33] Lennart Erik Nacke, Michael Kalyn, Calvin Lough, and Regan Lee Mandryk. 2011. Biofeedback Game Design: Using Direct and Indirect Physiological Control to Enhance Game Interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 103–112. DOI: `http://dx.doi.org/10.1145/1978942.1978958`

[34] Joel C Perry, Jacob Rosen, and Stephen Burns. 2007. Upper-limb powered exoskeleton design. *IEEE/ASME transactions on mechatronics* 12, 4 (2007), 408–417.

[35] Max Pfeiffer, Tim Dünte, Stefan Schneegass, Florian Alt, and Michael Rohs. 2015. Cruise control for pedestrians: Controlling walking direction using electrical muscle stimulation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 2505–2514.

[36] Kevin Ponto, Ryan Kimmel, Joe Kohlmann, Aaron Bartholomew, and Robert G Radwir. 2012. Virtual Exertions: a user interface combining visual information, kinesthetics and biofeedback for virtual object manipulation. In *3D User Interfaces (3DUI), 2012 IEEE Symposium on*. IEEE, 85–88.

[37] V Popescu, Grigore Burdea, and Mourad Bouzit. 1999. Virtual reality simulation modeling for a haptic glove. In *Computer Animation, 1999. Proceedings*. IEEE, 195–200.

[38] A. Pusch, O. Martin, and S. Coquillart. 2008. HEMP-Hand-Displacement-Based Pseudo-Haptics: A Study of a Force Field Application. In *2008 IEEE Symposium on 3D User Interfaces*. 59–66. DOI: `http://dx.doi.org/10.1109/3DUI.2008.4476593`

[39] Andreas Pusch, Olivier Martin, and Sabine Coquillart. 2009. HEMP – Hand-displacement-based pseudo-haptics: A study of a force field application and a behavioural analysis. *International Journal of Human-Computer Studies* 67, 3 (2009), 256 – 268. DOI: `http://dx.doi.org/10.1016/j.ijhcs.2008.09.015` Current trends in 3D user interface research.

[40] Michael Rietzler, Florian Geiselhart, Julian Frommel, and Enrico Rukzio. 2018a. Conveying the Perception of Kinesthetic Feedback in Virtual Reality using State-of-the-Art Hardware. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA. DOI: http://dx.doi.org/10.1145/3173574.3174034

[41] Michael Rietzler, Florian Geiselhart, Jan Gugenheimer, and Enrico Rukzio. 2018b. Breaking the Tracking: Enabling Weight Perception using Perceivable Tracking Offsets. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA. DOI: http://dx.doi.org/10.1145/3173574.3173702

[42] Michael Rietzler, Florian Geiselhart, and Enrico Rukzio. 2017. The Matrix Has You: Realizing Slow Motion in Full-body Virtual Reality. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology (VRST '17)*. ACM, New York, NY, USA, Article 2, 10 pages. DOI: http://dx.doi.org/10.1145/3139131.3139145

[43] Majed Samad, Elia Gatti, Anne Hermes, Hrvoje Benko, and Cesare Parise. 2019. Pseudo-Haptic Weight: Changing the Perceived Weight of Virtual Objects By Manipulating Control-Display Ratio. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 320, 13 pages. DOI: http://dx.doi.org/10.1145/3290605.3300550

[44] Eastman Kodak Company. Human Factors Section and Eastman Kodak Company. Ergonomics Group. 1986. *Ergonomic Design for People at Work: The design of jobs, including work patterns, hours of work, manual materials handling tasks, methods to evaluate job demands, and the physiological basis of work*. Vol. 2. Lifetime Learning Publications.

[45] Lior Shapira and Daniel Freedman. 2016. Reality Skins: Creating Immersive and Tactile Virtual Environments. In *Mixed and Augmented Reality (ISMAR), 2016 IEEE International Symposium on*. IEEE, 115–124.

[46] Adalberto L Simeone, Eduardo Velloso, and Hans Gellersen. 2015. Substitutional reality: Using the physical environment to design virtual reality experiences. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 3307–3316.

[47] Mandayam A Srinivasan, Gerald Lee Beauregard, and David L Brock. 1996. The impact of visual information on the haptic perception of stiffness in virtual environments. In *ASME Winter Annual Meeting*, Vol. 58. 555–559.

[48] Emi Tamaki, Takashi Miyaki, and Jun Rekimoto. 2011. PossessedHand: techniques for controlling human hands using electrical muscles stimuli. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 543–552.

[49] Dzmitry Tsetserukou, Katsunari Sato, and Susumu Tachi. 2010. ExoInterfaces: novel exosceleton haptic interfaces for virtual reality, augmented sport and rehabilitation. In *Proceedings of the 1st Augmented Human International Conference*. ACM, 1.

[50] Yasuyoshi Yokokohji, Yoshihiko Sugawara, Junji Kinoshita, and Tsuneo Yoshikawa. 2003. Mechano-Media that Transmit Kinesthetic Knowledge from a Human to Other Humans. In *Robotics Research*. Springer, 499–512.

[51] Xu Zhang, Xiang Chen, Yun Li, Vuokko Lantz, Kongqiao Wang, and Jihai Yang. 2011. A framework for hand gesture recognition based on accelerometer and EMG sensors. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans* 41, 6 (2011), 1064–1076.

[52] Xu Zhang, Xiang Chen, Wen-hui Wang, Ji-hai Yang, Vuokko Lantz, and Kong-qiao Wang. 2009. Hand gesture recognition and virtual game control based on 3D accelerometer and EMG sensors. In *Proceedings of the 14th international conference on Intelligent user interfaces*. ACM, 401–406.