Give Weight to VR: Manipulating Users' Perception of Weight in Virtual Reality with Electric Muscle Stimulation

Sarah Faltaous
University of Duisburg-Essen
Essen, Germany
sarah.faltaous@uni-due.de

Marvin Prochazka
University of Duisburg-Essen
Essen, Germany
marvin.prochazka@stud.uni-due.de

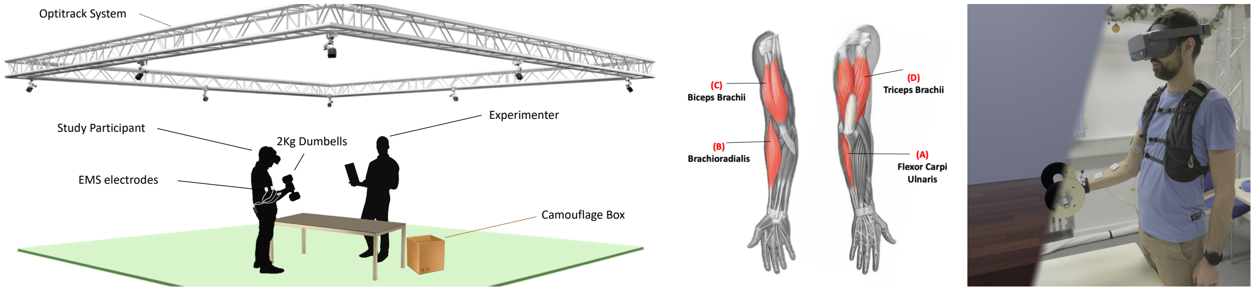
Jonas Auda
University of Duisburg-Essen
Essen, Germany
jonas.auda@uni-due.de

Jonas Keppel
University of Duisburg-Essen
Essen, Germany
jonas.keppel@uni-due.de

Nick Wittig
University of Duisburg-Essen
Essen, Germany
nick.wittig@uni-due.de

Uwe Gruenefeld
University of Duisburg-Essen
Essen, Germany
uwe.gruenefeld@uni-due.de

Stefan Schneegass
University of Duisburg-Essen
Essen, Germany
stefan.schneegass@uni-due.de



(a) (b) (c)

Figure 1: Study setup showing the the tracking system (i.e., Optitrack) used to map the real to the virtual world. The participant with electrical muscle stimulation pads on the targeted muscles. The Camouflage box to create the illusion of having multiple weights.

ABSTRACT

Virtual Reality (VR) devices empower users to experience virtual worlds through rich visual and auditory sensations. However, believable haptic feedback that communicates the physical properties of virtual objects, such as their weight, is still unsolved in VR. The current trend towards hand tracking-based interactions, neglecting the typical controllers, further amplifies this problem. Hence, in this work, we investigate the combination of passive haptics and electric muscle stimulation to manipulate users' perception of weight, and thus, simulate objects with different weights. In a laboratory user study, we investigate four differing electrode placements, stimulating different muscles, to determine which muscle results in the most potent perception of weight with the highest comfort. We found that actuating the biceps brachii or the triceps brachii muscles increased the weight perception of the users. Our findings lay the foundation for future investigations on weight perception in VR.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; **Virtual reality**; **Haptic devices**.

KEYWORDS

virtual reality, haptics, illusions, electric muscle stimulation

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1 INTRODUCTION

Nowadays, Virtual Reality (VR) environments provide a rich visual and auditory experience. Providing a rich haptic experience, however, is still challenging. This is amplified by the current trend towards direct interaction using hand tracking instead of the VR controller. Direct interaction has the advantage that it allows for more natural input such as grabbing or pushing of objects. However, currently, users receiving no haptic feedback.

Researchers investigate new ways of providing haptic feedback for direct interaction. This can be either passive haptics [7, 15, 24] or active haptics (e.g., using robots [14] or drones [6, 16]). Each of these approaches has its' own advantages and disadvantages. While drones and robots are rather expensive, passive haptics are more limited in terms of their flexibility: a passive haptic object can be used to generate haptic feedback for its virtual counterpart. Researchers, however, start addressing this limitation. Haptic retargeting, for example, allows the users to reuse the same physical object for multiple virtual ones by providing visual illusions [7]. Other extensions explore how well the passive haptic approach works for different sizes [4]. Another approach that can be used to provide haptic feedback throughout a direct interaction is using electrical muscle stimulation (EMS). EMS mimics the brain's signals to the muscles by inducing a current that results in a muscle contraction and subsequently a movement of a part of the body [33]. Research showed that this technology can be used to generate haptics out of the void in VR [21].

In this work, we focus on extending this approach for the objects' weight. We particularly look into how we can change the weight perception of users using electrical muscle stimulation (EMS). In contrast to earlier work, we combine EMS with the passive haptics approach to change the weight perception of user. Thus, we do not aim to generate a weight sensation but change the weight perception, that is, creating virtual objects that are perceived lighter or heavier than their actual physical counterparts. We compared the effect of actuating four different muscles in a laboratory study ($N = 10$). We found that particularly the biceps brachii, as well as the triceps brachii, muscles allow increasing the perceived weight.

2 HAPTICS AND WEIGHT PERCEPTION IN VIRTUAL REALITY

Since it is not feasible to provide objects of a large range of weights within VR applications, researchers investigate methods to manipulate the weight perception of objects in VR [21, 25, 31]. Niiyama et al. created an object containing liquid metal that can be pumped in or out of it [25]. Therefore, the object is capable of representing different weights dynamically. Other systems provide kinesthetic perceptions, like Zenner and Krüger's weight-shifting VR controller [40]. This system uses a rod with weights inside that can shift positions from the grip to the end to change the center of mass and change the perception of weight. Further weight-shifting devices like a controller that can be reconfigured dynamically to create various distributions of mass are explored. The controller presented by Shigeyama et al. uses different configurations to imitate the feeling of holding objects in VR [34]. Additional approaches utilize haptic devices using integrated weights. When shaking the device implemented by Yamamoto et al., the user senses the inertial force as the weight of the device as the accelerated weight inside is moving [38]. Grabity provides a weight illusion using vibrotactile feedback, uni-directional brakes, and asymmetric skin stretch [10]. Archibet et al. create haptic feedback in virtual reality using an elastic band. The band is attached to the shoulder of the user and provides feedback through resistance [1, 2]. Zenner and Krüger present a controller allowing to change the air resistance to create the illusion of weight when dragging objects [39]. Aero-plane system renders weight changes on a plane (e.g., baking pan) using propellers [18]. Besides the physical weight of an object, other aspects such as cutaneous (i.e., pseudo haptics) and proprioception feedback also influence the perception of weight [13, 22]. Another possibility is that instead of creating weight through real weights and forces visual and haptic stimuli can simulate weight in a virtual way that the user's brain interprets as the weight of an object as the overall perception is assembled from various senses [12]. Following this path, the idea arises that this effect could be even stronger in VR due to higher immersion and, therefore, more perceived spatial and sensory presence [8].

Rietzler et al. implement a software-based approach to weight perception based on an offset. In their approach, they nudge the users to raise their arms in the real environment higher than in VR, which increases the perceived weight of the held objects [31]. In further work, visual cues are exploited to create an illusion of weight through a mismatch between the virtual hand of an avatar and the position of the user's real hand. When the user pushes a moveable object, the virtual hand stops while the user's hand is moving beyond the virtual object in the physical space, creating a perception of resistance [30]. In another approach, the researchers manipulated the weight perception by manipulating the ease of moving an object in VR (e.g., heavier objects would be harder to move [32]. Jauregui et al. manipulate the weight perception of a user by using a virtual avatar that is altered according to prerecorded animations using motion capture [17]. Amplifying the movement of an object's virtual representation on screen creates a haptic illusion. The users perceive the weight of the moving object to be less [11]. Pusch et al. simulate wind resistance in VR by hand displacement [28, 29]. Furthermore, Zenner et al. [41] combined dynamic passive haptic feedback with haptic retargeting to create the illusion of changing weights.

Previous work mainly focused either on changing the physical weight of objects and applying forces, or tried to manipulate the user's weight perception through other senses. While the former is bound to complex hardware devices, the latter creates illusions usually based on a displacement of the virtual representation. In contrast, EMS is a promising approach since it can be used to directly influence the user's proprioception. Lopes et al. explored the integration of EMS in VR providing haptics to virtual objects as well as initial weight perception [21]. We extend this work by investigating in detail how the actuation of different muscles influences the weight perception.

3 USER STUDY

We conduct a user study to investigate how far EMS can enrich the haptic experience provided by passive haptics. In particular, we investigate the use of EMS to manipulate the perceived weight of passive haptics to adjust it to differently heavy objects. We strive to understand what muscles need to be actuated and what differences in weight can we achieve.

3.1 Scenario and Muscle Selection

To explore the potential of using EMS to manipulate the weight perception, we focus on a simple dumbbell biceps curl (DBC) as scenario. We chose this scenario because dumbbells can be easily grabbed and the weight can also be changed. DBC are mainly performed to train the biceps brachii, brachialis and brachioradialis muscles [23] (cf., Figure 1(b)). Since both the biceps brachii and brachialis are located in the upper arm, we picked the biceps brachii muscle from the upper arm and the brachioradialis muscle from the forearm. Also, depending on how the lifting action is done, the flexor carpi ulnaris muscle gets contracts in case of a wrist movement (e.g., when the hand turns inwards) [20]. While executing a biceps curl, the biceps muscle experience eccentric and concentric contractions [26]. In the eccentric contraction the triceps muscle, being the biceps antagonist, contracts [35]. Taking into account these facts and to have preliminary insights into which muscle would best alter the weight perception, we targeted four different muscles, for convenience we refer to them as conditions, namely; the flexor carpi ulnaris (A) and brachioradialis (B) from the forearm and biceps brachii (C) and triceps brachii (D) from the upper arm (cf., Figure 1(b)).

3.2 Apparatus and Setup

We prepared a 4x4 meter tracking space (cf., Figure 1(a)) with a table (50*100 cm) and a dumbbell (2 kg – as passive haptics) in the middle. Our main aim is to investigate the possibility of using EMS to manipulate weight perception. However, as discussed in previous work [3, 36, 37], the weight perception is influenced by the visual size of the objects that sets an expectation of the weight in brain. In our work, we focus only on the weight perception and therefore the use of a virtual reality was crucial to control the users’ visual input from being influenced with any presented real objects. Another aspect that was taken into consideration is the auditory input where, the user might establish that no weights were changed because the noise linked to changing the dumbbells were absent. Therefore, we implemented a virtual environment showing the same scene. Thus, the environment includes the same table (e.g., size, height) and the same dumbbell (e.g., width, handle thickness). Next to it, we placed a box with further dumbbells which were never used in the study, which we refer to in figure 1(a)) as the camouflage box. Throughout the study, we would be putting the same used 2kg dumbbell in and out of the box to create the auditory illusion that the dumbbells were actually changed.

We used an OptiTrack 13W optical tracking system to track the dumbbell, table, and the users hand using rigid bodies (cf., Figure 1(c)) to link the passive haptics and virtual environment. We also show a virtual hand representing where the users hand is to ease picking up the dumbbell. As soon as the user approaches the dumbbell, we fade out the virtual hand and start a countdown. After three seconds, a virtual shadow (30% opacity) of the dumbbell starts slowly moving upwards to provide direction and velocity cues to the user.

Additionally, we implemented a control application that connects to the Let-Your-Body-Move toolkit [27] that was placed with two EMS signal generators (Beurer Sanitas SEM 43 Digital EMS/TENS[1]) in a small backpack (see Figure 1(c)). The control application sends EMS feedback via the Let-Your-Body-Move toolkit. It controls the signal intensity and frequency that is sent to the targeted muscle. As our target is to manipulate the weight perception and not to initiate an action, as soon as the user lifts the dumbbell from the table the EMS signal is applied to the user. The signal then stops when the user has returned the dumbbell on the table again after completing a DBC.

3.3 Study Design

We conducted a within-subject study with the muscle (4 conditions: flexor carpi ulnaris (muscle *A*), brachioradialis (muscle *B*), biceps brachii (muscle *C*), and triceps brachii (muscle *D*)) as independent variable. As dependent variable we use self-reported feedback using 7-point Likert items regarding the perceived weight, the perceived intensity of the actuation, and perceived comfort rating of the actuation.

3.4 Participant and Procedure

We invited 10 participants to our lab aged 20 to 59 years old (Md = 29.5 years, SD = 12.5 years). Three participants self-identified as female and seven as male. After the participants arrived in the lab, we explained the purpose of the study and asked for their written consent, following our institutional ethical procedure. We explained the basic functionality of EMS and checked that they met the prerequisites as stated in the manual of the EMS signal generator. Next, we asked the participants to fill in a brief demographics questionnaire stating their age, gender. To remind the participants throughout the study of the positions of the electrodes, we marked a mannequin arm with the muscles labels (cf., Figure 1(b)): A, B, C, D. We then calibrated all four muscles using the EMS system. We started at a low intensity of 3μA and increased with a step of 2μA until an actuation happened. As soon as the actuation is clear (i.e., through an observed movement), we stopped the calibration process and noted the specific value. Next, we started the actual study in which we presented 2 dumbbells one after the other to the user. The user lifted each dumbbell once. While lifting, we actuated one muscle only at a time from the above-mentioned the four muscles or none as a baseline. After a dumbbell was lifted, we removed it from the table and tracking space and put it back onto the table. Overall, they lifted two times ten dumbbells, thus, each muscle got actuated four times. The conditions were counterbalanced to avoid any resulting patterns from actuating the same muscle sequence. The experimenter was noting down throughout the whole study the indications mentioned by the participant as well as any comment. In the end, the participants filled in a questionnaire that included questions regarding the weight perception, actuation intensity, and comfort level using 7 points Likert-item and a text field

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[1] https://sanitas-online.de/de/p/sem-43-digital-ems-tens/

question. The questionnaire contained each question four times – one per muscle. The study lasted on average around 60*mins* for every participant.

3.5 Results

Weight Perception Ratings. On 7-point Likert items (i.e., 1:decreased weight; 4:no influence on weight perception; 7:increased weight) the results show that actuating muscle A ($Md = 3, SD = 1.2$) reduces the perceived weight whereas muscle B ($Md = 4, SD = 1.0$) had no influence and muscle C ($Md = 6$, $SD = 1.7$) as well as muscle D ($Md = 5.5$, $SD = 0.66$) increase the perceived weight. A Friedman test shows statistically significant differences in the ratings, $\chi^2(3) = 8.935$, $p = .030$. Bonferroni corrected pairwise comparisons using Wilcoxon Signed Rank tests show that participants rated the perceived weight statistically significant higher for muscle D ($Md = 5.5$, $SD = 0.66$) compared to muscle A ($Md = 3$, $SD = 1.2$), $Z = -2.642$, $p = .048$. All other comparisons could not reveal a statistically significant differences ($p > .05$).

Intensity Rating. Asked about the intensity of the actuation, we found that participants rated muscle C ($Md = 6$, $SD = 1.0$) to have the most intense actuation, followed by muscle D ($Md = 4.5$, $SD = 1.5$) then muscle A ($Md = 4$, $SD = 1.7$) and muscle B ($Md = 3$, $SD = 1.1$). A Friedman test shows statistically significant differences in the ratings, $\chi^2(3) = 14.362$, $p = .002$. Bonferroni corrected pairwise comparisons using Wilcoxon Signed Rank tests show that participants rated the actuation intensity statistically significantly higher for muscle C compared to muscle B, $Z = -2, 825$, $p = .048$. All other comparisons could not reveal statistically significant differences ($p > .05$).

Comfortable Rating. Asked about the level of comfort, participants rated an actuation of muscle B ($Md = 5$, $SD = 1.5$) most comfortable, followed by muscle D ($Md = 4$, $SD = 1.4$), muscle C ($Md = 4$, $SD = 1.9$), and muscle A ($Md = 3.5$, $SD = 1.6$). A Friedman test could not show statistically significant differences in the ratings, $\chi^2(3) = 4.330$, $p = .228$.

Relation between Weight Perception and Actuation Intensity. Next, we explored the influence of intensity on weight perception. We found a positive correlation between actuation intensity and weight perception, showing that a more intense actuation is related to a perception of a higher weight, $r(38) = .353$, $p = .026$.

Relation between Weight Perception and Comfortable Rating. Last we investigated if a more comfortable actuation influences weight perception. A Spearman correlation could not reveal a significant relationship, $r(38) = .141$, $p = .385$.

Qualitative Feedback. Concerning the best weight perception participants rated the muscles differently with some of them segmenting the movement into start, middle, and end. P1 described that muscle *A* is *"strong at the lift and then decrease"* while muscle *"D [is] not strong at the start but strong when the arm is at 90 degrees."* Similar observations were noted by P2, P3, P8, P9 and P10. As they all differentiated their experience from the *beginning* to the point where their perception state changed let it be in the *"motion"* [P9] or at the end of the movement.

When asked about which actuated muscle felt natural, there was no conclusive reply. Three of the participants (P2, P3 ,and P4) mentioned that the feeling was not always natural as it doesn't *resist*[P4] the movement or induce a *"tingling"* feeling[P4]. Two participants reflected in general by describing the experience as *"very real"* [P9] and *"contributed to the immersion"* [P1]. The rest linked their weight perception to specific resulted movements like *"muscle B ...maintaining the natural shape of the hand"*[P5] while carrying the dumbbell, their own expectation of the system of making the weight *"heavier"*[P6].

When asked about their experience during the actuation they described as it as *"tingling"* [P2,P4], *uncomfortable* [P2,P8] and *moving arms after sleeping*[P7]. On one side, with the bigger part of them (N=6) describing it with no effect on the immersion in the VR with one describing it as *"surprisingly convincing"*[P1], two of them described it as *distraction* [P10] and *scary* [P6] linking that to the novelty effect. P5 also described the novelty aspect throughout the experience as she said that *"at the beginning, you feel it but then you become part of it"*. On the other side, two participants (P2 and P7) linked their level of immersion to the more comfortable actuation as for example P2 describing that *"muscle A and B were okay because not so strong"* and P7 *"muscle C... was too much"*.

4 DISCUSSION

Our results provide preliminary insights into weight manipulation using EMS. They show that using EMS is not only confined to changing actions [5] or communicating haptics feedback in VR [21] but also could be used to manipulate the perception of the weight of passive haptics. Participants indicated the biceps brachii (muscle *C*) induced the heaviest weight. This is in line with the literature stating that the muscle strength that influences the movement in the joint most is generated through the biceps brachii (muscle *C*) [9]. This is also the case for the dumbbell biceps curl scenario we used in the study [23]. However, the biceps brachii also resulted in the highest variance in weight perception with three participants also indicating that they perceived the weight actually lighter compared to the baseline. This indicates that instead of providing the sensation of an additional force applied to the arm, the actuation rather supported the lifting and, thus, it felt lighter. In contrast, we were able to change the weight perception by actuating the triceps brachii (muscle *D*) more consistently. All participants argued that the weight felt heavier. Along the same line, the triceps being the biggest muscle in the arm (i.e., length-wise) and the biceps antagonist [19] that contracts when we extend the arm at the elbow, it induced the second heaviest weight perception. We, therefore, conclude that in order to induce the heaviest weight perception, the biggest muscle connected to the moving joint should be targeted.

Furthermore, as indicated by our participants, the actuation should not be focused the whole time on one muscle. However, it has to be adapted to the movement. Again reflecting on the explored movement (i.e., DBC), the most two actuated muscles were biceps brachii (muscle *C*) and triceps brachii (muscle *D*). However, they do not contract simultaneously but rather depend on the direction of the forearm, where the biceps brachii (muscle *C*) contracts by in the upwards lifting movement and the triceps brachii (muscle *D*) contracts in the downwards movement. Therefore, we recommend segmenting the targeted movement and actuating the contracted muscle at each part of the movement.

Overall, we could not observe a pattern in the results linking the signal intensity perception to the comfort level, however, the participants indicated in their comments that the feeling of discomfort was linked to the feeling that the signal had its peaks of being *"too much"*[P7]. We, therefore, recommend using this approach for lightweight inducing.

Limitations We acknowledge the following limitations to our work. To start, we focused only on the weight perception of the participants, without reflecting on their performance under the different conditions (i.e., maximum joint angle). Therefore, we plan to explore the participants performance under the different conditions. Second, we only investigated a single scenario. While the scenario provides a clear foundation for investigating weight perception, other scenarios with different interactions need to be investigated.

5 CONCLUSION

In this work, we explore the use of electrical muscle stimulation to manipulate the weight perception of objects in virtual reality. We conducted a user study (N=10) in which participants perform dumbbells biceps curls while being actuated with EMS. We actuated four different muscles that based on the physiological background are linked to the arm movements. We found that actuating the biceps brachii and triceps brachii influences weight perception most. Both muscles are well suited to change the perception of weight. We conclude that EMS can be well used to change the weight perception. While actuating a single muscle already yields good results, combining different muscles in different parts of the movement seems to be a promising direction for future research.

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REFERENCES

[1] Merwan Achibet, Adrien Girard, Maud Marchal, and Anatole Lécuyer. 2016. Leveraging Passive Haptic Feedback in Virtual Environments with the Elastic-Arm Approach. *Presence: Teleoperators and Virtual Environments* 25, 1 (07 2016), 17–32. https://doi.org/10.1162/PRES_a_00243 arXiv:https://direct.mit.edu/pvar/article-pdf/25/1/17/1625617/pres_a_00243.pdf

[2] Merwan Achibet, Adrien Girard, Anthony Talvas, Maud Marchal, and Anatole Lécuyer. 2015. Elastic-Arm: Human-scale passive haptic feedback for augmenting interaction and perception in virtual environments. In *2015 IEEE Virtual Reality (VR)*. 63–68. https://doi.org/10.1109/VR.2015.7223325 ISSN: 2375-5334.

[3] Eric L Amazeen and Michael T Turvey. 1996. Weight perception and the haptic size–weight illusion are functions of the inertia tensor. *Journal of Experimental Psychology: Human perception and performance* 22, 1 (1996), 213.

[4] Jonas Auda, Uwe Gruenefeld, and Stefan Schneegass. 2021. Enabling Reusable Haptic Props for Virtual Reality by Hand Displacement. In *Mensch Und Computer 2021* (Ingolstadt, Germany) *(MuC '21)*. Association for Computing Machinery, New York, NY, USA, 412–417. https://doi.org/10.1145/3473856.3474000

[5] Jonas Auda, Max Pascher, and Stefan Schneegass. 2019. Around the (Virtual) World: Infinite Walking in Virtual Reality Using Electrical Muscle Stimulation. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–8.

[6] Jonas Auda, Nils Verheyen, Sven Mayer, and Stefan Schneegass. 2021. Flyables: Haptic Input Devices for Virtual Realityusing Quadcopters. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology* (Osaka, Japan) *(VRST '21)*. Association for Computing Machinery, New York, NY, USA, Article 40, 11 pages. https://doi.org/10.1145/3489849.3489855

[7] 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* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 1968–1979. https://doi.org/10.1145/2858036.2858226

[8] Frank Biocca, Jin Kim, and Yung Choi. 2001. Visual Touch in Virtual Environments: An Exploratory Study of Presence, Multimodal Interfaces, and Cross-Modal Sensory Illusions. *Presence: Teleoperators and Virtual Environments* 10, 3 (06 2001), 247–265. https://doi.org/10.1162/105474601300343595 arXiv:https://direct.mit.edu/pvar/article-pdf/10/3/247/1623684/105474601300343595.pdf

[9] Yi-Wen Chang, Fong-Chin Su, Hong-Wen Wu, and Kai-Nan An. 1999. Optimum length of muscle contraction. *Clinical Biomechanics* 14, 8 (1999), 537–542. https://doi.org/10.1016/S0268-0033(99)00014-5

[10] Inrak Choi, Heather Culbertson, Mark R. Miller, Alex Olwal, and Sean Follmer. 2017. Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 119–130. https://doi.org/10.1145/3126594.3126599

[11] L. Dominjon, A. Lecuyer, J.-M. Burkhardt, P. Richard, and S. Richir. 2005. Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.* 19–25. https://doi.org/10.1109/VR.2005.1492749

[12] Marc O. Ernst and Heinrich H. Bülthoff. 2004. Merging the senses into a robust percept. *Trends in Cognitive Sciences* 8, 4 (2004), 162–169. https://doi.org/10.1016/j.tics.2004.02.002

[13] Christos Giachritsis, Rachel Wright, and Alan Wing. 2010. The Contribution of Proprioceptive and Cutaneous Cues in Weight Perception: Early Evidence for Maximum-Likelihood Integration. In *Proceedings, Part I, of the International Conference on Haptics: Generating and Perceiving Tangible Sensations - Volume 6191*. Springer-Verlag, Berlin, Heidelberg, 11–16. https://doi.org/10.1007/978-3-642-14064-8_2

[14] Zhenyi He, Fengyuan Zhu, and Ken Perlin. 2017. PhyShare: Sharing Physical Interaction in Virtual Reality. In *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology*. New York, NY, USA. https://doi.org/10.1145/3131785.3131795

[15] Ken Hinckley, Randy Pausch, John C. Goble, and Neal F. Kassell. 1994. Passive Real-World Interface Props for Neurosurgical Visualization. In *Conference Companion on Human Factors in Computing Systems* (Boston, Massachusetts, USA) *(CHI '94)*. Association for Computing Machinery, New York, NY, USA, 232. https://doi.org/10.1145/259963.260443

[16] Matthias Hoppe, Pascal Knierim, Thomas Kosch, Markus Funk, Lauren Futami, Stefan Schneegass, Niels Henze, Albrecht Schmidt, and Tonja Machulla. 2018. VRHapticDrones: Providing Haptics in Virtual Reality through Quadcopters. In *Proceedings of the 17th International Conference on Mobile and Ubiquitous Multimedia* (Cairo, Egypt) *(MUM 2018)*. Association for Computing Machinery, New York, NY, USA, 7–18. https://doi.org/10.1145/3282894.3282898

[17] David Antonio Gomez Jauregui, Ferran Argelaguet, Anne-Helene Olivier, Maud Marchal, Franck Multon, and Anatole Lecuyer. 2014. Toward "Pseudo-Haptic Avatars": Modifying the Visual Animation of Self-Avatar Can Simulate the Perception of Weight Lifting. *IEEE Transactions on Visualization and Computer Graphics* 20, 4 (2014), 654–661. https://doi.org/10.1109/TVCG.2014.45

[18] Seungwoo Je, Myung Jin Kim, Woojin Lee, Byungjoo Lee, Xing-Dong Yang, Pedro Lopes, and Andrea Bianchi. 2019. Aero-Plane: A Handheld Force-Feedback Device That Renders Weight Motion Illusion on a Virtual 2D Plane. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 763–775. https://doi.org/10.1145/3332165.3347926

[19] Rebecca L Johnson. 2004. *The Muscular System*. Lerner Publications.

[20] Vojtech Kunc, Michal Stulpa, Georg Feigl, and David Kachlik. 2019. Accessory flexor carpi ulnaris muscle with associated anterior interosseous artery variation: case report with the definition of a new type and review of concomitant variants. *Surgical and Radiologic Anatomy* 41, 11 (2019), 1315–1318.

[21] 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* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 1471–1482. https://doi.org/10.1145/3025453.3025600

[22] Anatole Lécuyer. 2009. Simulating Haptic Feedback Using Vision: A Survey of Research and Applications of Pseudo-Haptic Feedback. *Presence: Teleoperators and Virtual Environments* 18, 1 (02 2009), 39–53. https://doi.org/10.1162/pres.18.1.39 arXiv:https://direct.mit.edu/pvar/article-pdf/18/1/39/1624884/pres.18.1.39.pdf

[23] Giuseppe Marcolin, Fausto Antonio Panizzolo, Nicola Petrone, Tatiana Moro, Davide Grigoletto, Davide Piccolo, and Antonio Paoli. 2018. Differences in electromyographic activity of biceps brachii and brachioradialis while performing three variants of curl. *PeerJ* 6 (2018), e5165.

[24] John C. McClelland, Robert J. Teather, and Audrey Girouard. 2017. Haptobend: Shape-Changing Passive Haptic Feedback in Virtual Reality. In *Proceedings of the 5th Symposium on Spatial User Interaction*. New York, NY, USA. https:

//doi.org/10.1145/3131277.3132179

[25] Ryuma Niiyama, Lining Yao, and Hiroshi Ishii. 2014. Weight and Volume Changing Device with Liquid Metal Transfer. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (Munich, Germany) *(TEI '14)*. Association for Computing Machinery, New York, NY, USA, 49–52. https://doi.org/10.1145/2540930.2540953

[26] Liliam F Oliveira, Thiago T Matta, Daniel S Alves, Marco AC Garcia, and Taian MM Vieira. 2009. Effect of the shoulder position on the biceps brachii EMG in different dumbbell curls. *Journal of sports science & medicine* 8, 1 (2009), 24.

[27] Max Pfeiffer, Tim Duente, and Michael Rohs. 2016. Let Your Body Move: A Prototyping Toolkit for Wearable Force Feedback with Electrical Muscle Stimulation. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Florence, Italy) *(MobileHCI '16)*. Association for Computing Machinery, New York, NY, USA, 418–427. https://doi.org/10.1145/2935334.2935348

[28] Andreas Pusch, Olivier Martin, and Sabine 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. https://doi.org/10.1109/3DUI.2008.4476593

[29] 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. https://doi.org/10.1016/j.ijhcs.2008.09.015 Current trends in 3D user interface research.

[30] Michael Rietzler, Florian Geiselhart, Julian Frommel, and Enrico Rukzio. 2018. 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* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174034

[31] Michael Rietzler, Florian Geiselhart, Jan Gugenheimer, and Enrico Rukzio. 2018. Breaking the Tracking: Enabling Weight Perception Using Perceivable Tracking Offsets. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173702

[32] 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* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300550

[33] Stefan Schneegass, Albrecht Schmidt, and Max Pfeiffer. 2016. Creating User Interfaces with Electrical Muscle Stimulation. *Interactions* 24, 1 (dec 2016), 74–77. https://doi.org/10.1145/3019606

[34] Jotaro Shigeyama, Takeru Hashimoto, Shigeo Yoshida, Taiju Aoki, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2018. Transcalibur: dynamic 2D haptic shape illusion of virtual object by weight moving VR controller. In *ACM SIGGRAPH 2018 Posters*. ACM, Vancouver British Columbia Canada, 1–2. https://doi.org/10.1145/3230744.3230804

[35] The Healthline Editorial Team. 2018. Triceps anatomy, origin & function | body maps. https://www.healthline.com/human-body-maps/triceps#1

[36] Vonne van Polanen and Marco Davare. 2015. Sensorimotor Memory Biases Weight Perception During Object Lifting. *Frontiers in Human Neuroscience* 9 (2015). https://doi.org/10.3389/fnhum.2015.00700

[37] Vonne van Polanen, Robert Tibold, Atsuo Nuruki, and Marco Davare. 2019. Visual delay affects force scaling and weight perception during object lifting in virtual reality. *Journal of Neurophysiology* 121, 4 (2019), 1398–1409. https://doi.org/10.1152/jn.00396.2018 arXiv:https://doi.org/10.1152/jn.00396.2018 PMID: 30673365.

[38] Takeshi Yamamoto and Koichi Hirota. 2015. Recognition of weight through shaking interaction. In *2015 IEEE World Haptics Conference (WHC)*. IEEE, 451–456. https://doi.org/10.1109/WHC.2015.7177753

[39] André Zenner and Antonio Krüger. 2019. Drag:On: A Virtual Reality Controller Providing Haptic Feedback Based on Drag and Weight Shift. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300441

[40] André Zenner and Antonio Krüger. 2017. Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy to Enhance Object Perception in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 23, 4 (April 2017), 1285–1294. https://doi.org/10.1109/TVCG.2017.2656978 Conference Name: IEEE Transactions on Visualization and Computer Graphics.

[41] André Zenner, Kristin Ullmann, and Antonio Krüger. 2021. Combining Dynamic Passive Haptics and Haptic Retargeting for Enhanced Haptic Feedback in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 27, 5 (2021), 2627–2637. https://doi.org/10.1109/TVCG.2021.3067777