Flexing Muscles in Virtual Reality: Effects of Avatars' Muscular Appearance on Physical Performance

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ABSTRACT

Virtual reality (VR) allows users to embody any possible avatar. Previous work found that the appearance of avatars can change our perception and behavior. Such behavioral changes based on stereotypical assessments are known as the Proteus effect. Exergames involve physical activities of players, however, it is currently unknown if behavioral changes caused by an avatar's appearance can affect players' performance in physically engaging tasks. Therefore, we conducted a study with 30 participants to determine the effect of avatars' muscularity on physical performance and perception of effort. We found that participants in muscular avatars had a lower perceived exertion during an isometric force task. Furthermore, male participants embodying a muscular avatar had a higher grip strength. Results suggest that embodying avatars associated with power and strength can decrease the perception of effort and enhance physical performance. We discuss how body ownership, user identification, and gender moderate avatars' effects.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**.

KEYWORDS

virtual reality; Proteus effect; avatar embodiment; body ownership illusion; physical performance; muscular appearance

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1 INTRODUCTION

With the release of the Nintendo Wii in 2006 the popularity and interest in *exergames* – games that require the users to be physically active to play them – has increased. In contrast to common video game interaction as a sedentary activity, where playing video games is similar to watching TV, in exergames, e.g. Nintendo's commercially successful game Wii Fit [61], the players need to interact by predefined arm gestures or body motion. These motions are transmitted by controllers and are used as player input. As exergames are video games for exercising [27, 98], this type of game does not solely rely on players' physical motion as part of the interaction mechanics for the in-game experience. They also aim at improving the players fitness beyond the gaming context. Previous work found that players of a dancing exergame can have average heart rates between 137 and 148 beats comparable with an aerobic exercise [34, 49, 85, 100]. This energy expenditure can result in significant calorie burn [49], weight loss [83, 87], and an improved overall fitness [35]. Furthermore, exergames can reduce perceived pain [16], improve attendance [92], and physical performance [39]. Since games are an immensely popular and universal form of entertainment, the combination of gaming and physical exercise is promising for engaging the population to increase physical activity and promote a healthier lifestyle. The relevance of exergames has increased as we live in a time where obesity and physical inactivity is a major health concern in many parts of the world.

The advent of VR provides new possibilities to design exergames with novel interaction mechanics. Previous studies have already shown that VR exergames encourage physical activity [25], enhance motivation [37, 65] and support physical rehabilitation [22]. Current VR systems can enhance user experiences by fully immersing users into a 3D virtual environment (VE) through a head-mounted display (HMD) allowing them to interact from "within" the digital world. Through *avatars* – the digital representation of the users in a VE – one can experience an increased sense of *presence* – the feeling of being and acting in the VE [32, 95] – resulting in a more natural and intensive perception of presented stimuli [7, 88]. Beyond that, VR systems in combination with motion capture technology are able to accurately track user's limbs and body movement and synchronously transfer motions onto the virtual rendering of the avatar. As shown in prior experiments, this synchronous correlation of visual and proprioceptive information can induce the illusion of perceptually owning a virtual body. Consequently, the users accept the avatar as a virtual alter ego [3, 5, 18, 40, 91].

Previous work found that the appearance of the own avatar in VR can change behavior according to the user's stereotypical assessments. Alluding to the versatility of the Greek god, such behavioral changes have been coined the *Proteus effect* [102]. This effect occurs when salient characteristics of the avatar are associated with knowledge and experiences gained by anticipated entities. Reinhard et al. [72], for example, showed that embodying older-looking avatars reduces walking speed after exposition in VR. The activated stereotype of older-looking people walking slowly primes the user and unconsciously affects walking speed [72]. The Proteus effect can also improve cognitive user performance [5], decrease racial bias [33, 67], and increase appearance-based self-confidence [101].

However, little is known about the effects of avatars on physical performance and the perception of effort that are of particular interest for exergames. Matsangidou et al. [55] showed that immersive VR can reduce the perceived pain and effort when completing isometric bicep curls. Additionally, prior investigations also found that controlling avatars with what the authors call "overweight" decreases physical activity [66, 68] or performance [51] of players in a non-immersive exergame. These results suggest that avatars can affect physical activity and the user's performance, however it is yet unknown whether and how embodying avatars with different muscular appearance in an immersive VR experience influence physical performance and perceived exertion.

Changes of the users' behavior pose an opportunity for VR designers to deliberately utilize the Proteus effect to motivate and engage the users and to make them perform better than they would in a casual virtual embodiment. Particularly in exergames, where putting more effort in tasks potentially results in enhanced exercise benefits, the use of certain avatars could contribute to more effective and successful exergames. Thus, we investigated whether and how avatars with different muscular appearance affect users' physical performance and their perception of effort. In a study, 30 participants embodied three avatars with different muscularity. We found that participants embodying a muscular avatar had a lower perceived exertion during an isometric force task. We also show that male participants in a muscular avatar had a higher grip strength compared to those avatars with little and medium muscularity. We assume that the sensitivity to weight discrimination depends on the visual appearance of the avatar. Based on the findings, we discuss how body ownership, user identification, and gender moderate effects caused by the visual appearance of avatars.

2 RELATED WORK

Our work is based on a body of work showing avatars' effects on users in VR applications and games. We discuss underlying mechanisms of such effects and present previous investigations that cover essential aspects of the Proteus effect.

2.1 Body Ownership Illusion

Due to the plasticity of the human brain, we can experience a perceptual illusion of owning body parts or even an entire body other than our own - the *body ownership illusion* (BOI). In the well-known *rubber hand illusion*, for example, people experience a prosthetic rubber hand as their own while the artificial and the hidden real hand were synchronously stroked [15]. Petkova and Ehrsson [69] revealed that this illusion can also be induced for an entire body through visual and tactile correlations. BOIs could also be elicited in VR by spatially substituting the users' real body through an avatar so that they perceive the virtual environment from a first-person perspective (1PP) [53, 79, 81]. In VR, this illusion is typically created through 1PP and visuotactile [79], visuomotor [5, 40] or visuoproprioceptive [80, 81] stimulation of the users' sensory system [41].

Researchers assume that the BOI is based on the combination of multiple sensory cues into a unified percept [24]. Motion capture systems, for example, register users' limbs and transfer their motion onto the virtual skeleton of the avatar. When the user moves a limb, the corresponding virtual limb is moving accordingly in real-time. This synchronous multisensory stimulation allows the users to integrate the fused percept into their own body schema [24] and lets them even accept virtual bodies fundamentally different from their real bodies. Previous work showed that users reported an illusory sensation of owning virtual avatars that indicate to be much younger [3], older [5], or that have a different skin color [4, 33, 67] than themselves. As a function of the body ownership, the participants even change their behavior and attitude due to the virtual body. Initial studies investigating the embodiment of nonhumanoids found that users can even experience subjective embodiment of animals [1, 47], however, there is little known about objective correlates of owning these type of avatars such as behavioral changes.

Prior research presents various methods to measure BOIs in VR experiences. Beside physiological measures [45, 105], motor responses [29, 42, 75], cortical activity [57], and breaks in illusions [45], behavioral measures are a further approach to objectively provide evidence for the BOI to occur. Llobera et al. [53], for example, modulated the BOI by visuomotor synchrony and asynchrony, and determined the sensitivity towards temperature changes. Results show that the temperature sensitivity threshold negatively correlates with the BOI and that it can be a potential predictor for this phenomenon. On the contrary, Schwind et al. [78] could not find a systematic relationship between the degree of perceived body ownership and tactile sensitivity. This is in line with Matsumiya [56] who analyzed the "proprioceptive drift" as a behavioral measure [75] and revealed that body localization via haptics and the subjective sensation of body ownership are two distinct processes. These ambiguous findings demonstrate that still little is known about the underlying mechanisms of the BOI. In combination with objective measures for quantifying body ownership, questionnaires are a common instrument that is used to assess the subjective experience of embodiment.

2.2 Proteus Effect

Embodying an avatar can activate a top-down process that triggers behavioral, attitudinal, and perceptual changes in users. These changes that are caused by specific characteristics of avatars which are associated with previous knowledge and experiences about characters or stereotypes are attributed to the Proteus effect [101, 102]. Yee and Bailenson [101] revealed that users behave more self-confidently in terms of interpersonal distance and self- disclosure in a VR dialogue when embodied in an attractive avatar. Similar phenomena were shown in a second study, where users embodying taller avatars negotiated more aggressively and confidently in a VR bargaining task [101]. This could be explained by self-perception theory [8]. Users observe and evaluate themselves from an imaginary third-person perspective and infer their behavior according to common expectations [101]. As attractiveness and body height are associated with confidence, extraversion and self-esteem, users behave conform to the avatars' salient characteristics of identity.

In a meta-analysis, Ratan et al. [71] showed that the Proteus effect has been evidenced in a broad variety of contexts and concluded that it is a valid phenomenon with a small to medium effect size. Banakou et al. [4] have documented, for example, that the embodiment of dark-skinned avatars by light-skinned participants reduces implicit racial bias and that this post-embodiment effect could still be shown one week after the VR intervention. The connection of avatar stereotypes and user attitude was also illustrated by Yang et al. [99] who indicated that players with dark-skinned avatars played more aggressively in a non-immersive violent game than with light-skinned avatars. This is in line with common prejudices in participants' social context. Changes in player behavior after a 5-minute gaming experience could also be evidenced by Yoon and Vargas [103] and Rosenberg et al. [74] where players embodied in an heroic avatar exhibited more prosocial behavior. In another study, Banakou et al. [5] investigated whether embodying Albert Einstein as a stereotype for superior intelligence can affect the users' cognitive task performance. The authors showed that users embodied in Einstein performed significantly better in a playful cognitively demanding test than in a casual avatar. Overall, these results suggest that avatars can shape the interaction of users in VR games and applications, and affect their behavior and performance in the virtual environment and the real world after leaving VR.

2.3 Avatars' Effects in Exergames

Although behavioral and attitudinal changes through avatars have been shown in numerous contexts, little is known about the influence of avatars on physical performance. Li et al. [51] found that overweight children playing a Nintendo Wii exergame had a higher exercise motivation and in-game performance with a normal avatar compared to an overweight avatar. Peña and Kim [66] as well as Peña et al. [68] showed that players of a competitive virtual tennis game exhibited an increased physical activity with a normal avatar compared to an obese avatar. However, this effect is moderated by the body size of the opposing avatar. Similar was shown in studies by Barathi et al. [6] and Keenaghan et al. [40] who revealed that self-competing against idealized avatars can negatively affect physical performance in VR exergames. These studies examined the effect of avatars in a competitive exergame, where players compete against an unathletic or idealized avatar in a tennis match or a bicycle race. Hence, these results can not be considered in isolation from mutual influences of multiple avatars present in the virtual environment. Effects that are caused, for example, by competition [58] or behavioral confirmation [82, 101] can mediate the effect of avatars on the user. As already identified by previous work [44], it remains unclear whether and how avatars affect the embodied user's performance in physical tasks when being alone in VR.

2.4 Summary

Related work found that the embodiment of avatars associated with specific characteristics can affect users' perception, attitude and behavior. However, it is unknown whether and how avatars of different muscular appearance can influence users' physical performance and perception of effort in immersive VR. Based on the Proteus effect exergame designers could utilize avatars associated with power and strength to increase users' performance in physically engaging tasks. This could improve user's in-game performance and result in enhanced exercise benefits, since the users would be able to put more effort in physical tasks.

3 METHODS

We investigate whether the visual appearance of an avatar can be altered in a way that users will perform better in physical tasks when their virtual appearance indicates to be physically stronger. Furthermore, effects on weight perception, the self-perceived fitness, the sense of presence as well as body ownership were assessed.

3.1 Study Design

To investigate the effect of avatars' muscular appearance on users' physical performance and their perception of effort, we used a mixed-design with the between-subjects variable Gender and the within-subjects variable Body with the three levels *non-muscular*, *medium* and *muscular*. Thus, particpants embodied avatars of their own gender with different muscular appearance. To reduce order effects we counterbalanced the avatars using a 3 × 3 Latin Square.

3.2 Stimuli

We used three male and three female avatars with different muscular appearance (see Figure 1). We designed the avatars using the 3D-suite Daz3D[1]. We used the characters Genesis 8 Male and Genesis 8 Female and adapted their muscular appearance by morph targets[2]. For the male and female avatars, we defined the standard Genesis 8 Male and Female avatar as our stimuli with medium muscularity. We estimated the avatars' body weight based on the formula by Buckley et al. [17]: According to the medium avatars' body measurements, an adult male would weigh 72kg and an adult female would weigh 64kg. Based on the measurements of the medium avatars, we increased the avatars' proportions using morph targets by approximately 34% muscle mass to obtain the muscular avatar, and decreased approximately 17% of muscle mass to create the non-muscular avatars with a constant body height. Each avatar model had the same skeleton with an identical configuration of bones. We used the game engine Unity3D (v. 2018.3.2f1) to implement the VR application. We designed a virtual scene consisting of a room with light walls, a table, a mirror with stereoscopic reflections, and a dumbbell stand.

[1] https://www.daz3d.com/
[2] https://www.daz3d.com/massive-morphs-for-genesis-8-male,
https://www.daz3d.com/massive-morphs-for-genesis-8-female-s

Figure 1: 3D models of the avatars with different muscular appearance. The three avatars on the left were embodied by male participants, whereas the three avatars on the right were embodied by female participants. The avatars have a non-muscular, medium and muscular body (from left to right).

3.3 Measures

We took several measures to determine the effect of the independent variable. We measured the perceived exertion during an isometric force task using the established *Rating of perceived exertion* (RPE) scale [12]. We assessed the grip strength using a dynamometer as force measuring device. We also measured the *Just Noticeable Difference* (JND) using a psychophysical test with a constant stimulus and five comparison stimuli in a *two alternative forced choice task* (2AFC). Furthermore, participants were asked to fill in a self-appraisal questionnaire to determine the self-perceived fitness (SPF) [21]. Additionally, we quantified the sense of presence with the single item G1 of the IPQ questionnaire [76] and assessed the body ownership illusion with the body representation questionnaire (BRQ) [3, 5] after each condition. In line with Schwind et al. [77], all questionnaires were filled in the VR environment. Since we assumed that the task to assess the grip strength and the isometric force task to quantify the perceived exertion could affect the sensitivity to weight discrimination, we decided for a constant order of tasks in each condition and started with the psychopohysical test to determine the JND, measured the grip strength afterwards and finally assessed the perceived exertion.

3.3.1 Perceived Exertion. We investigated the perceived exertion during a force task with isometric muscle contractions. According to a standardized procedure [2, 36, 60], participants held one weight of 1kg in each hand for 60 seconds in a position at 90 degrees of shoulder abduction in the scapular plane (see Figure 2). Originally defined by Gunnar Borg [13] as "the feeling of how heavy, strenuous and laborious exercise is", we determined the perceived exertion during a physical exercise based on a popular and well-established experimental procedure [10, 12, 13]. We presented a virtual scale - the psychophysical Borg's RPE scale [12] - throughout the isometric force task. The RPE scale was designed to increase linearly with physical exercise intensity and consists of 15 grades from 6 to 20. Every second grade is combined with a textual representation of the intensity, e.g. "7" stands for "very, very light" and "19" for "very, very hard" [12]. An approximate estimation of the current heart rate can be calculated by multiplying each grade by 10, e.g. an intensity of 11 approximately matches a heart rate of 110. In the last five seconds of the task, the participants indicated their perceived exertion by orally communicating the grade that best represents their current perception of effort.

3.3.2 Grip Strength. Since grip strength correlates with overall muscle strength of a person [86, 94], we used grip strength as a dependent variable. Based on a standardized approach proposed by Roberts et al. [73] and the American Society of Hand Therapists [23], we created a task to assess participants' grip strength using a dynamometer for force measurement. In a standing position, participants adducted and neutrally rotated the shoulder of the dominant hand holding the dynamometer with the elbow flexed at 90 degrees (see Figure 2). The non-dominant arm was in a neutral, dangled position. Participants were not aware about the outcome of the measurements.

3.3.3 Just Noticeable Difference. The JND is a psychophysical measure that stands for the amount of a change in a stimuli to be detectable and noticeable [97]. Also referred as the difference threshold, we implicitly identified the JND in a 2AFC for weight perception to investigate the sensitivity to weight. We applied the method of constant stimuli [28, 43] based on the procedure by Wallace et al. [90], in which the participants estimated weight pairs where one always had a constant weight. The constant weight was 200g whereas the comparison weights were 205g, 210g, 215g, 220g and 225g. The participants were presented the constant weight and a comparison weight in a randomized order. On each trial, the participants lifted the two weights in succession and held them for three seconds with their left hands, as the left side of the human body is more sensitive to the perception of changes in weights [59]. After lifting and putting down the second weight, they immediately had to decide which of the two weights appeared to be heavier. After each response, a new weight pair was presented randomly. In total, each weight pair was compared six times in a randomized order so that three times the constant weight and three times the comparison weight was presented first. This procedure resulted in 30 weight comparisons. Based on Schwind et al. [78], who found an effect of limb ownership on the JND, we hypothesize that the JND while embodying a muscular or non-muscular avatar differs from the JND while embodying a medium avatar. We assume that the variation of the degree of the body ownership due to the muscular appearance of avatars changes user's weight perception.

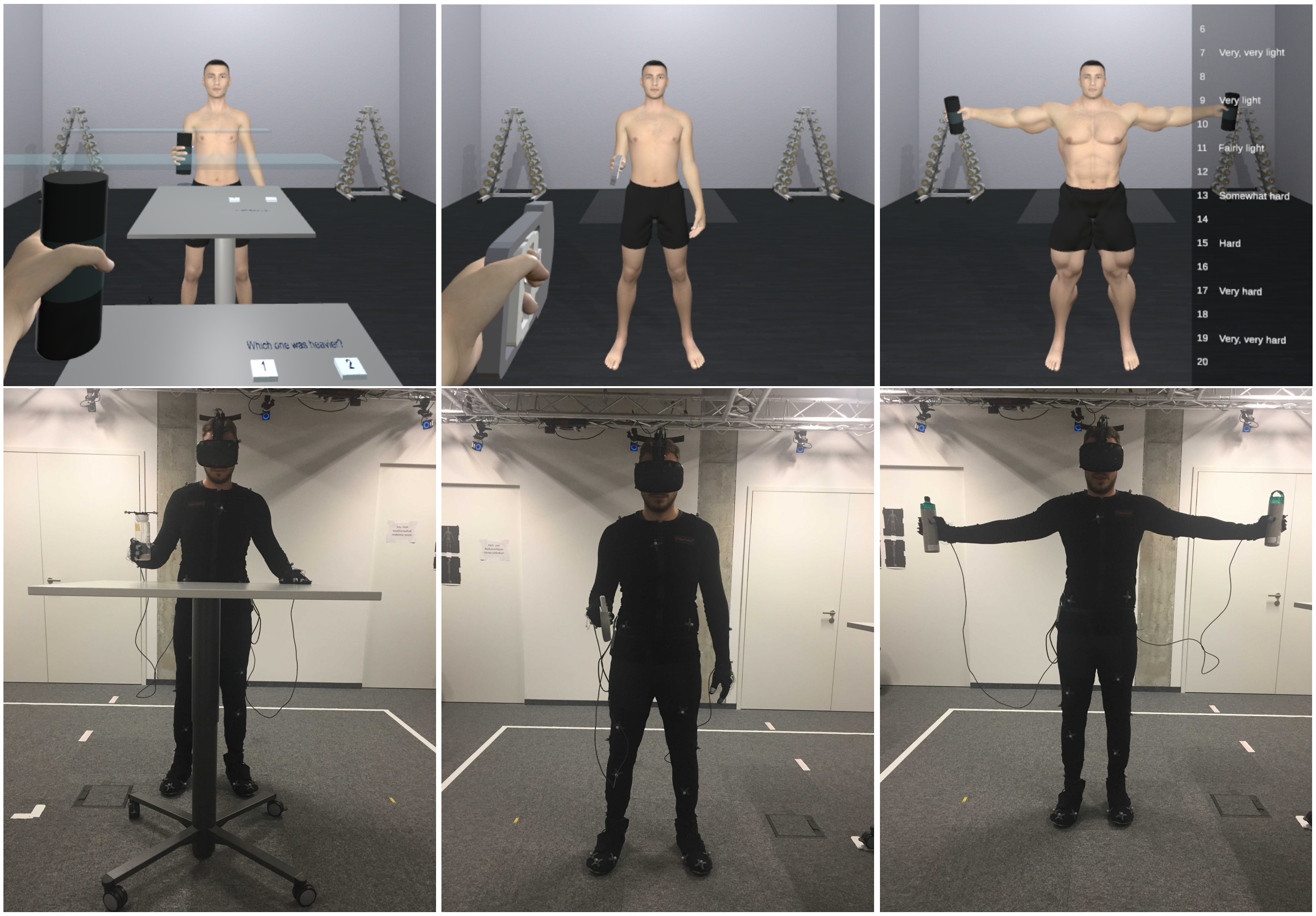

Figure 2: Participants in the virtual world from a first-person perspective during the tasks while looking in the mirror (top) and the corresponding real world (bottom). Participants performed three tasks: the JND task, the grip strength task and the isometric force task with shoulder abduction (from left to right).

3.3.4 *Self-Perceived Fitness.* We investigated the effect of different muscularity of avatars on the SPF using a version of the self-appraisal questionnaire from Borg and Skinner [11] adapted by Delignieres et al. [21]. The authors created a questionnaire with the five dimensions endurance, strength, flexibility, body composition and fitness rated on a 13-points scale with an ascending level from 1 to 13 [21]. Every second point consists of additional verbal expressions.

3.4 Apparatus

We defined an area (width: 4.2m, length: 3.9m) in our VR laboratory where participants could move during VR exposure. We induced the BOI by substituting the participant's real body through a non-muscular, medium and muscular avatar in VR using a HTC Vive HMD with a wireless adapter to allow participants moving freely within the VR area. The integrated Vive chaperone system rendered virtual lines when users approached the space boundaries preventing them to go beyond the defined VR area. The HMD has a wide horizontal field-of-view of 100° and a spatial resolution of 1080 × 1,200 pixels per eye displayed at 90 fps. Participants perceived the virtual body and the surrounding environment from 1PP. Through a virtual mirror the participants could constantly perceive their virtual body as their own.

We enhanced body ownership and agency by visuomotor synchrony. Participants' real movements were captured with Optitrack motion capturing[3] and transferred onto the virtual skeleton of the avatar. To track participants' full-body motion, we employed a marker-based OptiTrack motion tracking system with twelve cameras (eight PRIME 13 and four PRIME 13W) and the Motive software (v. 2.1). The motion tracking software ran on a dedicated PC with Windows 10, Intel i7-8700, 26GB RAM, and a NVIDIA GeForce GTX 1080 graphics card. We calibrated the OptiTrack system according to the manufacturer's specification and achieved an exceptionally precise calibration result (overall reprojection mean 3D error: 0.852mm, triangulation residual mean error: 0.8mm, overall wand mean error: 0.187mm, worst camera mean 3D error: 0.949mm).

[3]https://optitrack.com/

Participants had to wear black marker suits (Optitrack Motion Capture Suit Classic[4]) available in different sizes (S, M, and L) with 39 passive markers. Furthermore, they had to wear a pair of black gloves (100% cotton) with 16 active markers resulting in a total of 55 optical markers attached in a given pattern using velcro. To ensure accurate tracking of each individual finger, we used an active marker set (Optitrack active tag[5]) that consisted of 8 through-hole LEDs emitting a wide angle IR pulse. They were attached on the gloves by sewing each LED with 8 to 10 stitches onto each fingertip. The OptiTrack system tracked participants' skeleton with 240 fps and was synchronized with the HMD's head tracking to avoid interference. Using UDP multicast the skeletons were streamed through a local 1000 Mbit network connection via the NatNet protocol to the PC (Windows 10, Intel i7-8750H, 16GB RAM, NVIDIA GeForce GTX 1060 graphics card) that ran the VR application and rendered the 3D scene.

To create 8 physical weights, we used fine grained sand to fill ordinary beverage bottles made of plastic with screwcaps. We used 6 weights of 200g, 205g, 210g, 215g, 220g and 225g for the JND task. Additionally, we used 2 weights of 1kg for the isometric strength task. We modelled black virtual replicas of these weights each with a grey stripe in the center indicating the area participants should grip the weight. The physical weights were tracked using a rigidbody and were rendered in VR according to their real position. For the JND task, we used a table adjustable in height to ensure that each participant lifted the weights in succession in an identical lifting motion from the same position relatively to their body height. In VR, a virtual table was placed on a fixed position in the virtual scene. To measure grip strength we used a hand held dynamometer (Camry Digital Hand Dynamometer Grip Strength, Model EH101−37, China) with a digital display and an adjustable grip. We constructed an equivalent 3D model of the dynamometer with the 3D creation software Blender. To avoid tracking errors due to occlusion of the active hand markers by the dynamometer, we did not track the dynamometer with a rigidbody but integrated the 3D model into the skeleton of the avatars.

3.5 Participants

We recruited 30 participants (15m, 15f) via a mailing list of our institution. Their age ranged from 19 to 36 (M = 22.13, SD = 3.78). To assess the participants' level of fitness, we used the SPF questionnaire by Delignières et al. [21] as part of the demographics (see Table 1). All participants were compensated with one credit point for their study course. All of them had a technical background in computer science or engineering. One participant was left-handed. None of the participants reported any pain in the upper limbs before and after the study. This study received ethics clearance according to the ethics and privacy regulations of our institution and, thus, follow the policies of our country and funding body.

3.6 Procedure

Before entering the virtual environment, participants signed an informed consent form and filled in a demographic questionnaire. As part of the demographics, we assessed the participants' level of fitness. Afterwards, we provided a brief introduction into VR and the participants could get familiar with our VR system. We highlighted that the participants could withdraw or discontinue participation at any time without penalty or losing their compensation. After a short warm up including repeated shoulder abductions and adductions, we then supported the participants to put on the body tracking suit, the pair of gloves and the HMD which were already attached with optical markers. Before starting the scene, we adjusted the HMD to the participant's head and calibrated the inter-pupil distance to ensure best visual results. We adjusted the dynamometer grip to the participant's hand size based on a standardized procedure [26]. The physical table was adjusted to the participants' body height so that they could lay down the arms on the table in 90 degrees elbow flexion.

	Female (N=15)		Male (N=15)	
Scales of the SPF (min=1,max=13)	M	SD	M	SD
Fitness	4.86	2.50	5.00	2.00
Strength	6.46	1.68	5.93	2.68
Body Composition	6.86	2.03	6.53	2.44
Endurance	6.26	2.01	4.20	2.70
Flexibility	6.33	2.69	5.53	2.26

Table 1: Means (M) and standard deviations (SD) of the subscales of the SPF questionnaire by Delignières et al. [21]

After entering the scene, the participants had a one-minute exposition period to get accustomed with the avatar where they were instructed to stand in front of the mirror and perceive the virtual body while moving the limbs. After this, they were asked to perform the JND task by standing in front of the virtual table laying down the left arm onto the table in 90 degrees elbow flexion. The investigator placed each physical weight on a fixed position on the table right in front of the left arm of the participant. This was the starting position the participants lifted the weights from. The corresponding virtual weight was spawned when the real weight collided with a virtual trigger box surrounding the starting position. The participants lifted the weights to a predefined height indicated by a virtual blue bar. As soon as the virtual weight collided with the bar, the bar became red and turned blue again after three seconds. This indicated that the participant had to put down the weight back to the starting position. In a randomized order the investigator replaced each weight one after another. After each weight pair a virtual text appeared on the table in front of the participant with the following question: "Which one was heavier?". The participants had to guess by tapping one of two virtual buttons with a "1" indicating that the first presented weight was heavier, and a "2" that the second weight was perceived as heavier. After virtually pressing one of the two buttons, the next trial started by presenting a new pair of weights.

After the JND task, the investigator paused the VR application and the screen faded to black. The investigator handed over the dynamometer and restarted the VR application with a scene where the participants embodied the same avatar as before in the corresponding experimental condition with a virtual dynamometer in the equivalent hand. None of the participants noticed that the

[4]https://optitrack.com/products/motion-capture-suits/
[5]https://optitrack.com/products/active-components/

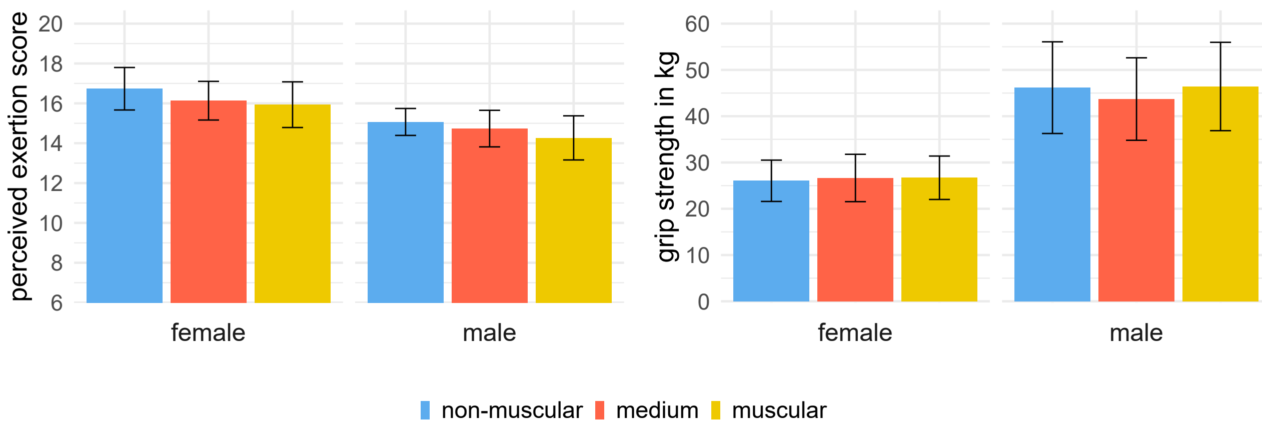

Figure 3: Average scores of the perceived exertion during the isometric force task (left) and the mean values of the grip strength measurements with a dynamometer (right). The error bars show the 95% confidence interval.

dynamometer was not tracked since we attached the virtual dynamometer onto the skeleton of the avatar and, therefore, the rotation and translation of the avatars' wrist bones were transferred onto the 3D mesh of the dynamometer. Hence, we successfully created the illusion of tracking the dynamometer. The participants were instructed to stand on a virtual sign on the floor in front of the mirror and squeeze the dynamometer as strong as possible for five seconds. In line with the Southampton protocol [73], the investigator instructed the participants with the words: "I want you to squeeze as hard as you can for five seconds". I will say stop after five seconds". The investigator started the task with a simple "Go". After five seconds, the investigator paused the VR application, took the dynamometer, handed over two weights for the left and right hand and started a new scene.

In the isometric force task, the participants were instructed to remain at the same location in front of the mirror and to laterally raise the shoulder until the arms were slightly above horizontal. This position should be kept for 60 seconds holding both weights in the left and right hand maintaining a good posture in an upright position. The virtual RPE scale was presented throughout the task placed at the wall next to the virtual mirror. After 55 seconds the investigator asked the participants to indicate their physical exertion. Afterwards, the investigator paused the VR application, took both weights and started a scene with the next avatar to proceed with an one-minute exposition time. Each task was performed in a standing position. Neither verbal encouragement nor visual feedback regarding the performance outcome were given during the tasks. The participants spent about 45 minutes in VR resulting in a total time of approximately 60 minutes for the study.

4 RESULTS

Our measures consist of non-parametric data. Shapiro-Wilk tests for normality was used to determine the assumption of normal distribution of all measures. Results show violations of normality for all measures ($p < .05$). Hence, we used the ARTool package for R by Wobbrock et al. [96] to apply an aligned rank transform (ART) analysis of variance (ANOVA) for hypothesis testing of non-parametric data. Items of the body representation questionnaire (BRQ) concern ordinal data. Participation was entered as a random factor in all analyses. All pairwise cross-factor comparisons are Bonferroni corrected.

4.1 Perceived Exertion

An ART multifactorial mixed design ANOVA revealed a significant effect of Gender, $F(1, 28) = 4.476$, $p = .043$, $\eta_p^2 = .137$, and Body, $F(2, 56) = 3.978$, $p = .024$, $\eta_p^2 = .124$, on perceived exertion, however there was no interaction effect of Gender × Body, $F(2, 56) = .576$, $p = .565$, $\eta_p^2 = .020$. Although we found main effects of Gender and Body, pairwise comparisons using Wilcoxon signed-rank test were not able to reveal significant differences within Gender and Body (all $p > .05$). Hence, we additionally performed two univariate ART ANOVAs within the two independent groups *male* and *female*. There was no significant effect between the Body levels of *male*, $F(2, 28) = 2.963$, $p = .068$, $\eta_p^2 = .174$ and of *female*, $F(2, 28) = 1.906$, $p = .167$, $\eta_p^2 = .119$. Thus, this is in line with the results of the ART multifactorial mixed design ANOVA.

Additionally, we performed a multi-variate linear regression analysis of each subdimension of the BRQ and could not find a significant effect of the subdimensions, $p = .869$, on participants' perceived exertion.

4.2 Grip Strength

An ART multifactorial mixed design ANOVA revealed a significant effect of Gender, $F(1, 28) = 21.084$, $p < .001$, $\eta_p^2 = .429$, and Body, $F(2, 56) = 3.430$, $p = .039$, $\eta_p^2 = .109$, on grip strength. There was no interaction effect of Gender × Body, $F(2, 56) = 1.338$, $p = .271$, $\eta_p^2 = .045$. Although we found main effects of Gender and Body, pairwise comparisons using Wilcoxon signed-rank test were not able to reveal significant differences within Gender and Body (all $p > .05$). Hence, we additionally performed two univariate ART ANOVAs within the two independent groups *male* and *female*. Here, we found a significant effect between the Body levels

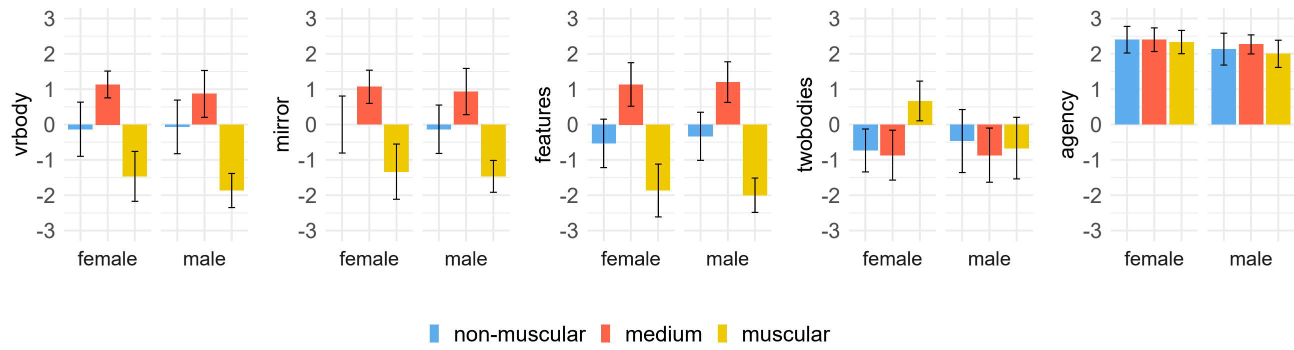

Figure 4: BRQ questionnaire scores on body ownerhsip for each subdimension (vrbody, mirror, features, twobodies, agency). The error bars show the 95% confidence interval.

of *male*, $F(2, 28) = 4.12$, $p = .027$, $\eta_p^2 = .227$ and not of *female*, $F(2, 28) = 1.525$, $p = .235$, $\eta_p^2 = .098$. Subsequent pairwise comparisons using Wilcoxon signed-rank test revealed significant differences between male *muscular* and male *medium* avatars, $p = .014$, however no significant differences were found in other pairwise comparisons (all $p > .05$). Thus, we assume an interaction effect between Gender × Body and suppose a Type II error in the ART multifactorial mixed design ANOVA.

Additionally, we performed a multi-variate linear regression analysis of each subdimension of the BRQ and could not find a significant effect of the subdimensions, $p = .223$, on male participants' grip strength.

4.3 Just Noticeable Difference

We used the R package quickpsy Linares and López-Moliner [52] to fit psychometric data using Weibull cumulative distribution function (2 free parameters, 0% lapse rate). We considered the constant stimulus (200g) as the point of subjective equality (PSE) assuming a 50% probability of a correct response at chance (the 50% criterion value). We applied a maximum-likelihood model as fitting criteria with a 75% threshold as the JND. This is the threshold at which participants correctly decided for the heavier weight in 75% of the trials. To estimate the 95% confidence intervals, we performed a non-parametric bootstrap with 1000 trials [52]. Figure 5 depicts the psychometric functions for each condition. A comparison of the means indicates a lower JND for the *muscular* avatar (M = 20.62g, SD = 2,03) compared to the *non-muscular* (M = 22.62g, SD = 4.19) and *medium* (M = 22.62g, SD = 5.67) avatar. Since previous work showed that the JND of males and females do not differ relatively [30], we calculated the JNDs combining the data of male and female subjects per condition. Due to the number of samples per participant, we could not fit a function to obtain individual JNDs and, therefore, we did not perform any inferential statistical analysis. Consequently, we only provide descriptive statistics.

4.4 Self-Perceived Fitness

An ART multifactorial mixed design ANOVA could not show a significant effect Gender, $F(1, 28) = 1.047$, $p = .315$, $\eta_p^2 = .036$ on fitness, however there was a significant effect of Body, $F(2, 56) = 7.034$, $p = .001$, $\eta_p^2 = .200$. We did not find an interaction effect of Gender × Body, $F(2, 56) = .343$, $p = .711$, $\eta_p^2 = .012$. Pairwise comparisons using Wilcoxon signed-rank test within Body found a significant effect of the *non-muscular* and *muscular*, $p = .016$, and *medium* and *muscular*, $p = .012$, avatars. We did not find any further effects of Gender and Body on the subscales endurance, strength, flexibility and body composition (all $p > .05$). Participants perceived themselves as physically fitter embodying the *muscular* avatar than the *non-muscular* and *medium* avatar (see Figure 6).

4.5 Body Ownership

To detect significant differences in the illusion of body ownership for each avatar, we performed multiple ART multifactorial mixed design ANOVAs on each subscale of the BRQ. We did not find a significant effect of Gender, $F(1, 28) = .148$, $p = .702$, $\eta_p^2 = .005$, on the subscale vrbody, however we found a significant effect of Body, $F(2, 56) = 29.772$, $p < .001$, $\eta_p^2 = .515$. There was no interaction effect of Gender × Body, $F(2, 56) = .450$, $p = .639$, $\eta_p^2 = .015$. Pairwise comparisons using Wilcoxon signed-rank test within Body revealed significant differences between *non-muscular* and *medium* ($p = .010$), *non-muscular* and *muscular* ($p = .002$), and *medium* and *muscular* ($p < .001$) avatars.

Gender, $F(1, 28) = .036$, $p = .850$, $\eta_p^2 = .001$, had no significant effect on mirror, however we found a significant effect for Body, $F(2, 56) = 30.770$, $p < .001$, $\eta_p^2 = .523$. There was no interaction effect Gender × Body, $F(2, 56) = .111$, $p = .895$, $\eta_p^2 = .003$. Pairwise comparisons using Wilcoxon signed-rank test within Body showed significant differences between *non-muscular* and *medium* ($p = .003$), *non-muscular* and *muscular* ($p = .001$), and *medium* and *muscular* ($p < .001$) avatars.

We found no significant effect of Gender on features, $F(1, 28) = .033$, $p = .856$, $\eta_p^2 = .001$, however there was a significant effect of Body, $F(2, 56) = 48.427$, $p < .001$, $\eta_p^2 = .523$. We did not find an interaction effect of Gender × Body, $F(2, 56) = .095$, $p = .908$, $\eta_p^2 = .003$. Pairwise comparisons using Wilcoxon signed-rank test within Body showed significant differences between *non-muscular* and *medium* ($p < .001$), *non-muscular* and *muscular* ($p < .001$), and *medium* and *muscular* ($p < .001$) avatars.

We found no significant effect of Gender on twobodies, $F(1, 28) = .490$, $p = .489$, $\eta_p^2 = .017$, however there was a significant effect of Body, $F(2, 56) = 6.094$, $p = .004$, $\eta_p^2 = .178$. We find an interaction effect of Gender × Body, $F(2, 56) = 5.984$, $p = .004$, $\eta_p^2 = .176$. Pairwise comparisons using Wilcoxon signed-rank test revealed significant differences between female *medium* and female *muscular* ($p = .009$), and female *non-muscular* and female *muscular* ($p = .005$). There were no significant differences between all male avatars (all $p < .05$).

There was neither a significant effect of Gender, $F(1, 28) = .911$, $p = .347$, $\eta_p^2 = .031$, Body, $F(2, 56) = .818$, $p = .446$, $\eta_p^2 = .020$, nor an interaction effect of Gender × Body, $F(2, 56) = .061$, $p = .940$, $\eta_p^2 = .002$, on agency.

4.6 General Presence

We performed an ART multifactorial mixed design ANOVA and did not find a significant effect of Gender on general presence, $F(1, 28) = 3.910$, $p = .057$, $\eta_p^2 = .122$, however there was a significant effect of Body, $F(2, 56) = 6.451$, $p < .003$, $\eta_p^2 = .187$. We also found an interaction effect of Gender × Body, $F(2, 56) = 3.214$, $p = .047$, $\eta_p^2 = .102$. Pairwise comparisons using Wilcoxon signed-rank test revealed a significant difference between male *medium* and male *muscular* ($p = .038$). Other pairwise comparisons were not significant (all $p > .05$). Male participants felt less present in the virtual environment when embodying the *muscular* avatar compared to the *medium* avatar (see Figure 6).

5 DISCUSSION

The data of our experiment showed a significant effect of avatars' muscular appearance on users' perceived exertion during physical effort. Furthermore, we found that male participants embodied in a muscular avatar had a higher grip strength compared to being in a medium avatar in immersive VR.

To explain these effects, we refer to prior research that supports the notion that the type of the avatar's body triggers expectations of what it would be like to own such a body [3, 5]. Since the brain is able to adapt to changes in the body structure to compensate the discrepancy between the real and the avatar's body, and to integrate the "new" body features into the own body schema [53, 57], we accept the virtual body as our own and behave in accordance to common expectations connected to the type of body [101]. Since participants embodied in a muscular avatar are expected to perform better in physical tasks than in avatars with a less muscular body physique [84], we assume that their "new self" motivates and engages the users and, therefore, increases physical performance in terms of perceived exertion and grip strength.

In our study, we investigated the effect of avatars' muscular appearance when being alone in VR. In contrast to Barathi et al. [6] and Koulouris et al. [46], we have to consider our effects isolated from reciprocal influences of multiple avatars based on interactive feedforward methods. The authors have already identified *self-modelling* as an effective intervention procedure to enhance the players' physical performance in a competitive exergame, where players raced against their improved version. However, Koulouris et al. [46] also found that idealised avatars as competitors may even have a negative impact on players' performance. This is in line with Peña and Kim [66] who showed that physical activity can decrease when the players think that their avatar has an physical advantage or disadvantage over the opponents' avatar. They referred to it as the "take it easy" and "give up" hypothesis [66]. Thus, results from these studies imply that being and interacting with another avatar might have additional effects such as the impact of social presence, competition or self-discrepancy [46] that may confound embodiment effects caused by the visual appearance of avatars on physical performance. Due to the ambiguous findings from previous work, more research is needed to back up our results.

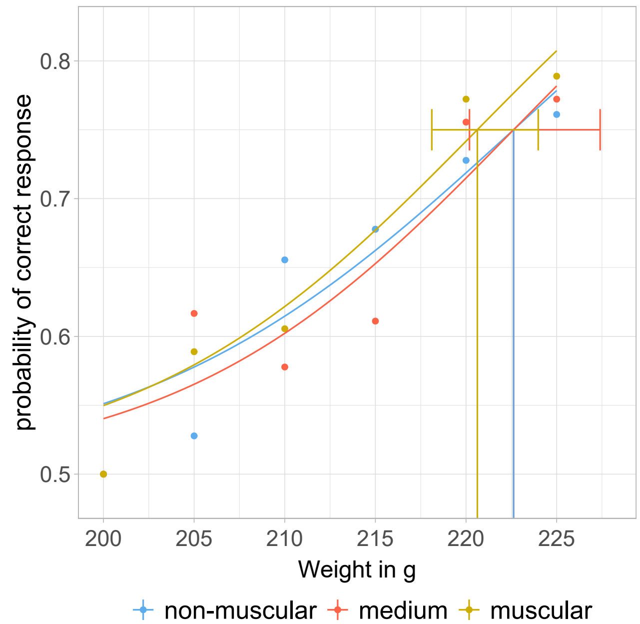

Figure 5: Psychometric functions and JNDs (75%) of all conditions based on the fitted Weibull cumulative distribution. The y-axis represents the probability to correctly choose the heavier weight. The error bars show the 95% confidence interval. Participants in the muscular avatar condition had a lower JND than in the non-muscular and medium condition.

5.1 Perceived Exertion

The perceived exertion during the isometric force task with shoulder abduction was assessed by the RPE scale. The ratings suggest that the task was less physically demanding for participants embodied in a muscular avatar. Even if they performed the same exercise, particpants perceived the task as more exhausting and physically intense embodied in a non-muscular avatar.

The findings suggest that the muscular appearance of avatars can systematically affect the conscious sensation of effort exerted during a physical exercise. Since the perception of effort can fundamentally determine pace and performance in physical tasks [20], endurance performance [63], adherence to exercise programs and physical acitivity [54, 64], this could pose an opportunity for exergame designers to decrease players' perceived exertion by changing the avatars' muscular appearance.

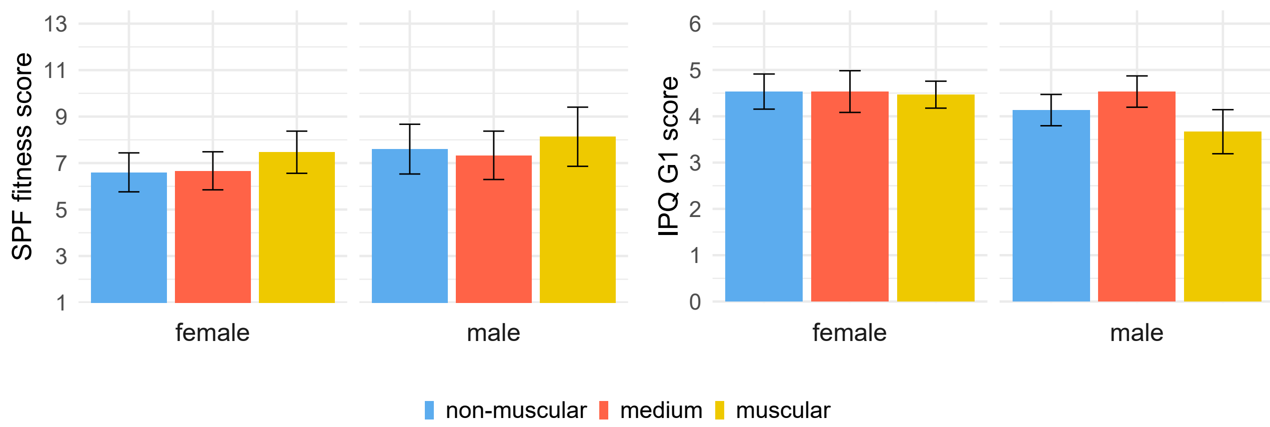

Figure 6: Average scores of the subscale fitness of the SPF questionnaire (left) and the general presence (item G1) of the IPQ (right). The error bars show the 95% confidence interval.

Based on the work by Wiemeyer [93], who created an interdisciplinary framework to evaluate the efficacy of fitness applications, further studies are needed to investigate whether the muscular appearance of avatars can be utilized to design more effective exergames.

5.2 Grip Strength and BOI

We could not find a systematic influence of muscular appearance of the avatar on grip strength. We hypothesized that the grip strength increases with the embodiment of our avatars from non-muscular to muscular, when in fact male participants embodied in the non-muscular avatar tended to have a higher grip strength than embodied in the medium avatar. Since previous work revealed that the extent of the illusion of body ownership can moderate the Proteus effect [1, 3, 62, 104], the induced BOI could potentially affect the grip strength. However, there was no effect of the body ownership ratings on grip strength and perceived exertion, that is why we assume that both measures are not functions of the experienced body ownership.

Considering the scores of the BRQ's subdimensions and the general presence which were generally low, we induced the strongest BOI and presence in the medium avatar indicating that the medium avatar most resembles the participants' physical body and their body physique, thus serving as an appropriate baseline. In line with the perceived exertion, we should have observed that participants embodied in the non-muscular avatar have a lower grip strength compared to that when embodied in the medium avatar, which was not the case. Equally high agency ratings for all avatars indicating a high sense of motor control rule out effects caused by technical limitations, for example tracking issues or drops in framerate.

A possible explanation why male participants embodied in the non-muscular avatar did not have a lower grip strength compared to the medium avatar could be the shape of the body and the connected associations of users. The SPF in our analysis serves as a manipulation check indicating that the muscular avatar was considered to be the fittest with the non-muscular avatar tending to have a better perceived fitness than the medium avatar. This is in line with our results regarding the measurement of grip strength. Hence, the non-muscular body type of the avatar could still be perceived as too fit and athletic due to low body fat rather than being associated with physical weakness. Future work should focus on conducting a study to determine what stimuli should be used to explicitly represent strength and power on the one hand, and physical weakness and the characteristic of being unathletic on the other hand.

5.3 Gender Differences in the Body Image

Interestingly, grip strength could not be enhanced for female participants by embodying a muscular avatar. According to self-perception theory, the evaluation of the avatar from an imaginary third-person perspective and the resulting associations have to be linked with the user's self to allow the Proteus effect to occur [8, 72, 101]. Koulouris et al. [46] showed in their study that women considered their athletic version of themselves as slimmer than that of male participants, who customized their avatars with a more muscular physique. This could be potentially explained by gender differences in the body image - the subjective perception and beliefs about the own body [19].

Previous work found that women evaluate the fitness of their own body in a different way than men [48]. The idealized image of the male body consists of extreme muscles and a lean body physique [14, 19, 50] with an ideal body about 13 kg more muscular than their own [70]. On the contrary, women tend to idealize a "curvaceously" thin body [31] with even negative emotions connected with athletic or hypermuscular bodies [89]. Even if the muscular avatar is perceived as physically fit according to the SPF, the features of the avatar's body may not be desirable for women causing a lack of engagement and excitement to a greater extent than normal. Hence, the idealized version of females perceived to be athletic and physically strong in a motivating manner seems not to match with our avatars, that is why we assume that the avatars' characteristics could not be connected with the user's self. Since user identification and wishful identification foster intrinsic motivation [9] resulting in a more motivated behavior and better performance [9, 38, 46, 91], the lack of identification with the female muscular and non-muscular avatar could be a factor that the avatars did not affect grip strength. Future work should analyze user identification and the BOI as moderators of embodiment effects caused by the avatar, since it is yet unknown how and in particular to what extent these concepts mediate effects on the embodying user. Therefore, objective measures to assess the participants' physical conditions such as the BMI and the body weight should be measured to complement subjective ratings such as the SPF.

5.4 JND

Based on results of prior work by Schwind et al. [78], who investigated the effect of virtual limb ownership in a visual-haptic integration task and found an effect of hand embodiment on the JND, we used the JND task to get first insights into the relationship of full body ownership and the sensitivity to weight discrimination. Descriptive statistics show that users embodied in muscular avatars had a higher sensitivity to weight discrimination than users owning a non-muscular or medium avatar. According to the BRQ ratings, participants indicated to have the lowest BRQ scores in the muscular body, thus we assume that the user's weight perception in VR could be affected by the variation of the degree of BOI due to the muscular appearance of avatars. Since our sample size does not allow inferential statistics on individual level, in future work we aim to repeat the experiment with a larger sample and individual JNDs to investigate whether the variation of the degree of body ownership changes user's weight perception.

6 CONCLUSION

In this paper, we investigated the effects of avatars with different muscular appearance on the perception of effort, physical performance and weight perception. 30 participants performed three different tasks. First, we investigated the sensitivity to weight discrimination by identifying the JND in a psychophysical experiment using a 2AFC task. Second, we measured the participants' grip strength using a dynamometer. Finally, we assessed the perceived exertion during an isometric force task. We also integrated questionnaires in VR to measure the SPF, the sense of presence and the BOI. We assume that the muscular appearance of avatars can affect the perceived exertion of the embodying users during physical tasks. Under the limitation that we could not find an enhancement of female participants' grip strength, results suggest that the avatars' muscular appearance can affect the physical performance for male users. More research is needed to consolidate the findings as they may provide an opportunity for designers of VR exergames to take advantage of the avatars' muscular appearance in short-time physical tasks to make players perform better than they would in a casual virtual embodiment. Hence, this could result in enhanced exercise benefits and contribute to more effective and successful exergames. Future work should also explore the contribution of concepts like body ownership, user identification and user motivation to get deeper insights into the underlying mechanisms.

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