

*Research Article*

The role of Haptic Feedback on Upper Extremity Muscle Activity, Perceived Exertion, and Presence in VR-Based Exergames

Elvina Arviningtyas¹, Khoirul Muslim^{1*}

¹Department of Industrial Engineering, Faculty of Industrial Technology, Institut Teknologi Bandung, Bandung, 40132, Indonesia

*Corresponding author: kmuslim@itb.ac.id; Tel.: +62-222504189

Abstract: Exergames based on virtual reality (VR) are widely adopted in upper extremity exercise and rehabilitation-related applications. However, VR-based strength training and the effect of haptic feedback remain underexplored. This study compared muscle activity and perceived exertion between conventional dumbbell exercise and VR-based training and examined the effects of different haptic vibration levels on muscle activity, perceived exertion, and presence of VR-based training. A within-subject design was employed with nine healthy female participants. Each participant completed two training conditions: conventional dumbbell exercise with weights of 1, 2, and 3 kg and VR-based exergames with three haptic vibration levels of 250, 240, and 230 Hz. Surface electromyography was used to assess muscle activity in the biceps brachii, triceps brachii, flexor carpi radialis, and extensor carpi radialis. Perceived exertion was rated using the Borg CR-10 scale, and presence was measured using the Barfield Presence Questionnaire. Data were analyzed using repeated-measures analysis of variance and nonparametric tests. The results showed that conventional training produced significantly higher and more load-sensitive muscle activity and perceived exertion than VR-based training. In the VR condition, the haptic vibration level significantly affected muscle activity, especially in the triceps brachii, but did not consistently affect perceived exertion or presence. In conclusion, controller-based vibrotactile feedback can modulate muscle activity during VR-based strength training but does not fully replicate the neuromuscular and perceptual demands of conventional resistance exercise. Therefore, the current VR-haptic system is better positioned as a low-load motor activation and engagement tool for early-stage rehabilitation than as a direct substitute for conventional progressive resistance training.

Keywords: Exergames; Haptic feedback; Muscle activity; Strength training; Upper extremities

1. Introduction

Virtual reality (VR)-based exergames have emerged as promising technologies for motor rehabilitation across various clinical conditions, including stroke. Stroke remains one of the ten leading causes of death worldwide, with mortality projected to increase from 6.5 million in 2020 to 9.7 million by 2050 (Feigin et al., 2023; World Health Organization, 2024). It is also a major cause of long-term disability, particularly because stroke-related brain injury can impair motor and cognitive functions and limit patients' ability to perform activities of daily living (Albert & Kesselring, 2012; Feigin et al., 2024). Upper-extremity impairment is particularly relevant because approximately 85% of stroke survivors experience persistent dysfunction in this region, which directly affects independence and quality of life (Hiroyuki et al., 2025; Nichols-Larsen et al., 2005).

Conventional rehabilitation approaches, including physiotherapy, occupational therapy, constraint-induced movement therapy, and mirror therapy, remain essential for restoring motor function after stroke. Constraint-induced movement therapy promotes the use of the paretic

limb through intensive and repetitive practice (Corbetta et al., 2015). In contrast, mirror therapy uses the visual reflection of the unaffected limb to create the illusion of movement in the affected limb (Thieme et al., 2018). However, conventional rehabilitation may become repetitive and monotonous, reducing motivation and long-term adherence. In this context, VR should not be positioned as a replacement for conventional therapy but as a complementary medium that can provide interactive, task-specific, repetitive, and feedback-driven exercises. These features are important because to stimulate neuroplasticity, post-stroke motor recovery requires intensive, repetitive, and task-oriented practice (Weiss et al., 2014).

VR-based exergames combine physical exercise with game-based virtual environments, enabling real-time feedback, adjustable task difficulty, performance monitoring, and more engaging rehabilitation experiences. Immersive VR may also simulate real-world environments and support flexible adaptation to user needs (Burdea, 2003; Weiss et al., 2006). For example, Navea et al. (2025) developed an adaptive VR pegboard game that calibrated rehabilitation tasks to each user's capabilities based on their shoulder range of motion. More broadly, a user-centered mobile game can support repetitive hand exercises as an accessible and engaging complementary tool for stroke rehabilitation (Octavia & Natasha, 2017). Within this context, VR-based exergames are relevant not only for clinic-based rehabilitation but also for broader digital health applications, including support for aging populations, home rehabilitation, remote therapy, and low-cost rehabilitation. Home-based stroke rehabilitation technologies may improve accessibility by enabling flexible training times and locations, remote therapist feedback, and support for patients with transportation barriers or limited access to rehabilitation services. However, their implementation still requires careful attention to usability, engagement, technical support, social context, and home-environment constraints (Chen et al., 2019). Safety is also an important consideration, as prolonged VR exposure has been linked to mild cybersickness and postural instability that may persist even after subjective symptoms subside (Pujiartati et al., 2020, 2024).

Several studies have reported the positive effects of VR-based exergames on upper-extremity rehabilitation after stroke. Immersive VR with hand tracking and visual feedback improves hand motor function, dexterity, and quality of life (Amin et al., 2024). Other studies have demonstrated the potential of VR, serious games, myoelectric pattern recognition, smart gloves, and 360° VR-based mirror therapy to support upper-limb rehabilitation through task-specific, repetitive, and feedback-rich exercises (Altukhaim et al., 2025; Hiroyuki et al., 2025; Jo et al., 2024; Muñoz-Novoa et al., 2025). VR combined with conventional rehabilitation improves upper-limb function, independence in daily activities, and brain connectivity in patients with stroke (Huang et al., 2024). Collectively, these findings indicate that VR-based exergames can enhance rehabilitation by increasing motivation, engagement, task repetition, and sensory feedback.

Despite these advances, most previous VR-based exergame studies have focused on task practice, motor control, visual feedback, or functional movement training, whereas strength-oriented VR exercise has been comparatively underexplored. Strength training can improve muscle activation, muscle strength, daily functioning, quality of life, and independence in stroke patients (Ada et al., 2006; Veldema & Jansen, 2020). Strength-focused interventions may also support motor recovery by increasing the activation of motor units and improving the coordination of force production (Folkerts et al., 2017; Griffin & Cafarelli, 2005). Therefore, it remains unclear whether VR-based exergames can move beyond engaging movement practice to elicit physiological responses comparable to those produced by physical resistance exercise.

Haptic feedback may play an important role in VR-based strength training because it can improve interaction realism and contribute to the perception of virtual object properties, including weight and resistance (Moosavi et al., 2023). However, realistic weight perception requires the integration of tactile and kinesthetic cues, including gravitational loading, body-level moments, fingertip pressure, friction, and movement-related feedback. Therefore, vibrotactile-only feedback may not be sufficient to realistically reproduce physical resistance (van Wegen et al., 2023). The role of haptic feedback in rehabilitation also remains inconsistent. Some

studies suggest that visual and auditory stimuli may dominate over haptic cues, whereas others indicate that tactile feedback can support motor recovery (Badde et al., 2020; Ernst & Banks, 2002; Kang et al., 2023; Kassuba et al., 2013; Kurzweg et al., 2024). Thus, the contribution of haptic feedback to physiological responses and perceived exertion during VR-based strength training remains unclear.

Another limitation of previous VR rehabilitation studies concerns the measurement of outcomes. Most studies have relied on clinical assessments or subjective questionnaires, such as the Fugl-Meyer Assessment, Action Research Arm Test, Box and Block Test, Manual Function Test, Modified Barthel Index, and Stroke-Specific Quality of Life (Amin et al., 2024; Jo et al., 2024). Some studies have incorporated kinematic measures to assess movement quality and motor learning (Altukhaim et al., 2025; Muñoz-Novoa et al., 2025). Although these outcomes are valuable for evaluating functional improvement, they do not directly indicate how muscles respond during training to simulated or perceived resistance. This limitation is particularly important in VR-based strength training because muscle activity reflects the physiological response to exercise intensity and load-related demands. Therefore, surface electromyography (sEMG) is required to objectively measure muscle activation during VR-based haptic exercise.

Based on these gaps, this study aims to compare the upper-extremity muscle activity and perceived exertion of conventional dumbbell-based strength training and VR-based exergame training. This study further examines whether different haptic feedback levels modulate muscle activity, perceived exertion, and presence in VR. The evaluated muscles include the biceps brachii, triceps brachii, flexor carpi radialis, and extensor carpi radialis. This study advances exergame research by integrating objective sEMG measurement with perceptual and experiential outcomes to determine whether VR-haptic parameter variation can produce load-sensitive physiological and perceptual responses.

This research involved healthy adult participants to evaluate the VR-based exergame design under controlled experimental conditions before future implementation in stroke rehabilitation. Healthy participants were selected to examine the effects of haptic feedback on muscle activity and perceived exertion without confounding factors related to neurological impairment. Therefore, the findings should be interpreted as preliminary evidence of neuromuscular and perceptual responses to VR-based haptic exercise, rather than as direct evidence of clinical effectiveness in patients with stroke. Muscle activity was measured using sEMG, perceived exertion was assessed using the Borg CR-10 scale, and presence was evaluated using the Barfield Presence Questionnaire.

2. Methods

2.1 Study design

This study was conducted at the Work System Engineering and Ergonomics Laboratory, Institut Teknologi Bandung, Indonesia, using a within-subject repeated-measures experimental design over four weeks. Each participant completed two experimental conditions: a conventional dumbbell-based strength training session using weights of 1, 2, and 3 kg and a VR-based exergaming session using vibration frequencies of 250, 240, and 230 Hz. The experimental procedure began with the conventional dumbbell session and continued with the virtual reality (VR)-based session.

A minimum interval of 48 h separated the sessions to minimize potential order and carryover effects, particularly muscle fatigue. The order of conditions within both the dumbbell and VR training sessions was randomized using within-block randomization to control for learning effects (Silva & Laje, 2024). Data collection was conducted on weekdays between 09:00 and 17:00 to maintain procedural consistency and ensure that measurements were performed during normal daytime activity hours. This time window was selected to reduce excessive physiological variability that could arise from testing at very early morning or late evening times. Both the dumbbell and VR sessions for each participant were scheduled within the same time window of

09:00–17:00 to ensure comparability between the two conditions. Nevertheless, time-of-day and circadian-related physiological variations may have occurred within this window.

2.2 Participants

Nine healthy female participants (age: 22.56 ± 2.13 years; body mass index [BMI]: 20.66 ± 1.15) without any neurological disorders were recruited for this study. Given the early-stage development of the VR-based exergame and haptic feedback configuration, this study was designed as a proof-of-concept investigation to examine initial physiological and perceptual responses under controlled laboratory conditions, rather than as a definitive clinical efficacy trial.

A preliminary pilot study involving three participants was conducted to estimate the effect sizes for sample size planning. Repeated-measures ANOVA on the pilot data yielded partial eta-squared values of $\eta_p^2 = 0.957$ for conventional dumbbell training and $\eta_p^2 = 0.707$ for VR-based training. Using the smaller estimate as input, G*Power (version 3.1; $\alpha = 0.05$, power = 0.80) indicated a minimum sample size of five participants, and nine participants were ultimately recruited. However, it must be acknowledged that the effect size estimates derived from only three pilot participants are inherently unstable and likely optimistic. The resulting minimum of five should not be treated as robust evidence of statistical adequacy. Therefore, the sample of nine participants is best understood as a feasibility-level decision consistent with the scope of this study's proof-of-concept.

During this early-stage evaluation, female participants were recruited to reduce sex-related variability in muscle activation, perceived exertion, body composition, and anthropometric characteristics. In addition, focusing on female participants provides preliminary relevance to a population reported to experience a substantial burden of stroke risk and post-stroke disability (Kelly-Hayes et al., 2003; Rexrode et al., 2022). However, this sex-specific recruitment strategy limits the generalizability of the findings to male participants and mixed-sex populations.

Participants were selected based on predefined inclusion and exclusion criteria. The inclusion criteria were as follows: (i) age between 18 and 25 years; (ii) regular aerobic exercise at least once per week; (iii) no history of neurological, stroke-related, or musculoskeletal disorders; (iv) absence of severe visual or hearing impairments; (v) no prior experience with strength training; (vi) right-hand dominance; (vii) normal body mass index (BMI); and (viii) no diagnosed mental disorders. The exclusion criteria were as follows: (i) a history of epilepsy, vertigo, or intolerance to VR devices; (ii) arthritis or pain in the arm or wrist that limited movement; (iii) prior familiarity with VR-based exergames; and (iv) current use of medications affecting the central nervous system.

Participant recruitment was conducted through the Institut Teknologi Bandung's academic network. An initial screening was conducted to assess eligibility against the inclusion criteria. All eligible participants provided written informed consent after receiving a detailed explanation of the study objectives and procedures. This study was approved by the Ethics Committee of Institut Teknologi Bandung (KEP/II/2025/X/M150825EA-EFHF) and was conducted in accordance with applicable ethical guidelines and regulations.

2.3 Experimental apparatus and materials used

2.3.1 Conventional dumbbell setup

In the baseline condition, participants performed conventional dumbbell strength training with 1 kg, 2 kg, and 3 kg dumbbells. The selection of dumbbells with weights of 1 kg, 2 kg, and 3 kg was based on Weber's Law, which states that the perception of weight differences depends on the ratio of change relative to the initial stimulus weight rather than on the absolute difference (Montag, n.d.). According to Montag (n.d.), the reference threshold for perceivable weight differences, known as the just noticeable difference (JND), is approximately 10% of the initial weight. Accordingly, for loads of 1 kg, 2 kg, and 3 kg, the minimum perceivable differences

are ± 0.1 kg, ± 0.2 kg, and ± 0.3 kg, respectively.

With a 1:2:3 ratio among the 1 kg, 2 kg, and 3 kg dumbbells, the relative difference between these load levels substantially exceeds the JND threshold, enabling participants to clearly perceive differences through proprioceptive sensory input. This selection of weights was also intended to avoid two extreme conditions: too small weight differences (e.g., 1 kg vs. 1.1 kg), which are difficult to perceive, and excessively large weight differences (e.g., 1 kg vs. 5 kg), which may impose undue burden or risk for participants.

2.3.2 Design of VR exergames and haptic parameter selection

In this study, the VR exergame system consisted of a head-mounted display (HMD) of the Meta Quest Pro, handheld VR controllers, and a Unity-based exergame environment. The system delivered visual, auditory, and vibrotactile feedback during the upper-extremity strength training tasks. The Meta Quest Pro controller uses a linear resonant actuator (LRA)-based mechanism to generate vibrotactile haptic feedback. Haptic stimulation was controlled by adjusting two parameters: vibration frequency and normalized amplitude. The controller did not provide force feedback or mechanical resistance; therefore, the haptic stimulus was used to approximate perceived weight rather than a physical dumbbell loading equivalent.

The haptic parameters were preset across three incremental intensity levels using a preliminary procedure. Two participants adjusted frequency–amplitude combinations and selected settings that they perceived as representing three haptic intensity levels. The resulting settings were defined as Haptic Level 1 (250 Hz, 10% normalized amplitude), Level 2 (240 Hz, 45% normalized amplitude), and Level 3 (230 Hz, 100% normalized amplitude). These levels are treated as operationally defined haptic intensity conditions and do not imply equivalence to the physical dumbbells' gravitational or inertial properties.

The physical rationale for the selected haptic settings was based on a sinusoidal vibration model, in which the peak acceleration can approximate the stimulus intensity, as shown in Equation (1):

$$a_{peak} = A(2\pi f)^2 \quad (1)$$

where A represents vibration amplitude and f represents vibration frequency. Because the controller output was normalized to the maximum actuator amplitude, the relative vibrotactile intensity of each haptic level can be approximated using Equation (2):

$$I_i \sim \alpha_i f_i^2 \quad (2)$$

where α_i is the normalized amplitude and f_i is the vibration frequency for the corresponding perceived weight level.

However, this presetting should be interpreted as a preliminary approximation of perceived weight rather than a complete psychophysical weight-perception model. VR-perceived heaviness may involve vibrotactile, visual, proprioceptive, grip-force, contact-pressure, and movement-related cues. Because the controller actuator generated vibrotactile cues without producing gravitational load, inertia, force feedback, or mechanical resistance, the selected haptic parameters were not intended to reproduce the physical forces generated by actual dumbbells. Instead, they were used to examine whether different levels of controller-based vibrotactile feedback could modulate muscle activity, perceived exertion, and presence during VR-based strength exercise.

The exergame system included a control panel that allowed the adjustment of the frequency and amplitude of the controller vibration, audio metronome settings, performance feedback audio, interset rest duration, number of sets, number of repetitions, and exercise type (Figure 1). The virtual environment included a virtual dumbbell, real-time hand motion tracking, an instructional avatar demonstrating the exercise movement, and a scoring system. An audio metronome set at 40 beats per minute (BPM) was used to standardize movement tempo across participants and conditions during all VR training sessions.

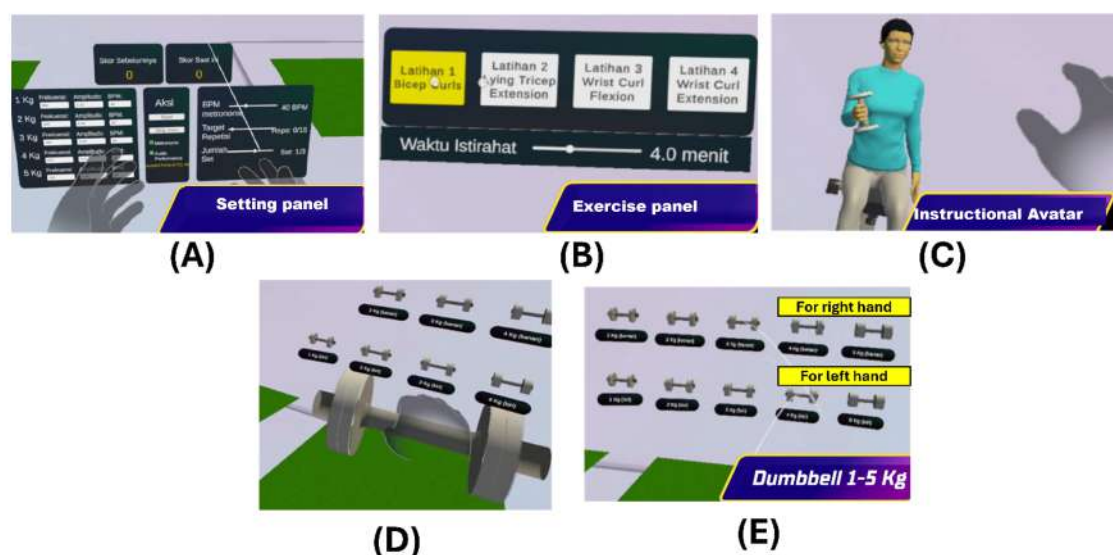


Figure 1 Exergames design. (A) Main setting panel. (B) Exercise settings panel. (C) Avatar demonstrating the exercises. (D) Virtual hand. (E) Virtual dumbbell

2.4 The experimental procedure

The experimental procedure began with the provision of standardized instructions. At the beginning of each session, the participants were asked to remove all body-worn electronic devices, such as smartwatches, to prevent potential noise or signal clipping in the sEMG recordings. Subsequently, the sEMG device was calibrated, and the system was set up. A warm-up session was then conducted, followed by the placement of sEMG electrodes on the biceps brachii, triceps brachii, flexor carpi radialis, and extensor carpi radialis muscles in accordance with the Hermens et al. (2000) and Barbero et al. (2012) guidelines.

The skin preparation procedure involved shaving fine hair from the electrode sites and cleaning the skin surface with alcohol swabs to reduce skin impedance and minimize sEMG noise before electrode placement. Subsequently, signal quality was inspected, and once a stable baseline and acceptable noise level were confirmed, MVC measurements were conducted. MVC was assessed because it is considered the gold standard for sEMG signal normalization (Fuentes del Toro & Aranda-Ruiz, 2025). The MVC procedures for the biceps brachii and triceps brachii followed the protocols described by Dürümlü et al. (2026), Rosa et al. (2024), and Roman-Liu and Bartuzi (2018). The MVC procedures for the flexor carpi radialis and extensor carpi radialis were performed as described by Akinola et al. (2020) (Figure 2). Each MVC trial lasted 5 s and was repeated 3 times, with a 2-min rest interval between repetitions.

Following the MVC assessment, the participants proceeded to the strength training session. Strength training comprised four exercises: biceps curl, lying triceps extension, wrist curl flexion, and wrist curl extension (Figure 3 and Figure 4). The biceps curl exercise was used to evaluate the biceps brachii muscle activation (Coratella et al., 2023). The lying triceps extension exercise was employed to assess the activation of the triceps brachii muscle (Yagiz et al., 2022). Wrist curl flexion was used to examine the activation of the flexor carpi radialis. Wrist curl extension was used to assess muscle activation of the extensor carpi radialis (American Council on Exercise, n.d.-a, n.d.-b). All four movements were performed in the seated or supine position. Each exercise was performed for three sets of 15 repetitions. The number of sets and repetitions was determined based on the recommendations of the American College of Sports Medicine (2009), which recommends performing strength training exercises with a minimum of 1 set of 8–12 repetitions. The participants were allowed to rest between sets until they felt sufficiently recovered to continue. Each intervention session lasted approximately 2.5 h.

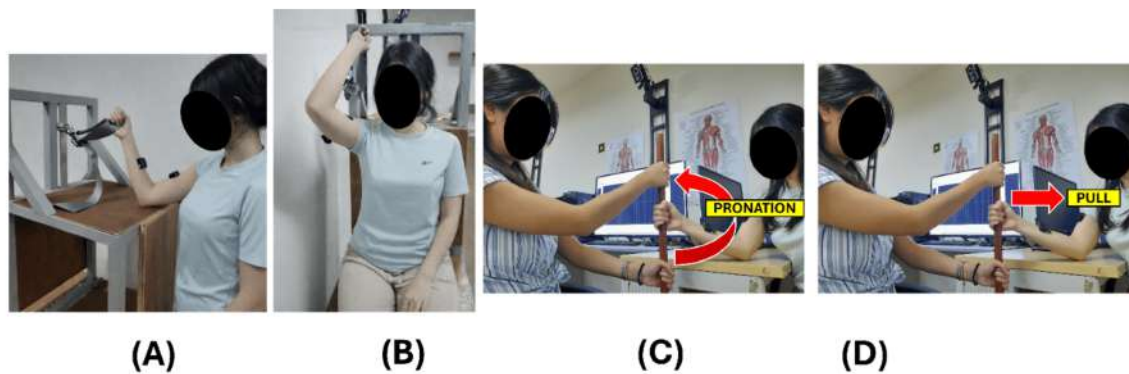


Figure 2 Maximum voluntary contraction (MVC) tasks for each muscle. (A) Biceps brachii. (B) Triceps brachii. (C) Flexor carpi radialis. (D) Extensor carpi radialis

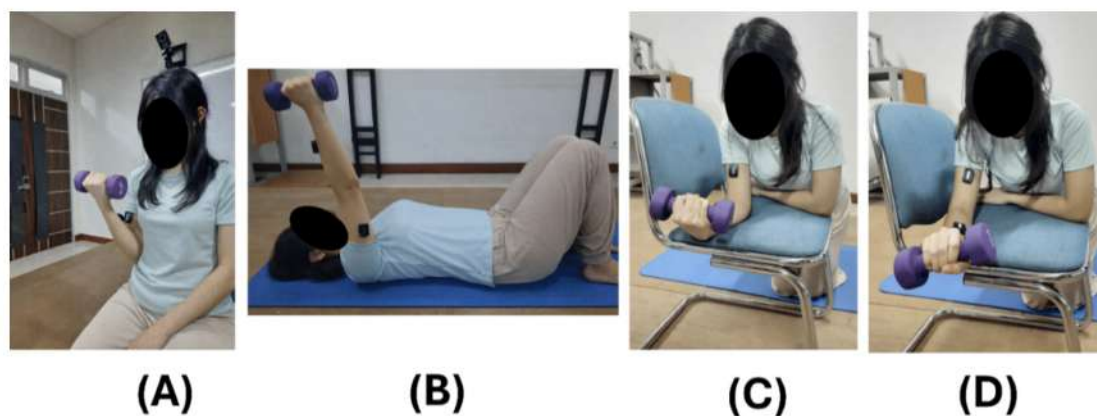


Figure 3 Conventional dumbbell training. (A) Biceps curl. (B) Lying triceps extension. (C) Wrist flexion curl. (D) Wrist extension curl

The procedures for the conventional dumbbell training and VR-based training sessions were largely identical, with the primary difference being the additional VR system setup required for the VR condition. The vibration frequency, amplitude, and metronome beat were configured according to the predefined parameters during the VR training session. The participants were given time to familiarize themselves with the visual environment and learn how to grasp the virtual dumbbell. If participants experienced discomfort or vertigo during the VR session, they were permitted to immediately remove the VR headset.

2.5 Outcome measures

Muscle activity was used as the primary outcome measure to examine the effects of conventional dumbbell strength training and virtual reality-based haptic training on neuromuscular responses. Muscle activity was assessed using sEMG on the wrist muscles (flexor carpi radialis and extensor carpi radialis) and arm muscles (biceps brachii and triceps brachii). Wrist and arm muscles were selected because they play a critical role in daily activities, such as grasping and holding objects (Skvortsov et al., 2025) and reaching movements (Barker et al., 2009). In addition, the extensor carpi radialis muscle was examined further because it has been identified

as a key indicator of hand function recovery in patients with stroke (Skvortsov et al., 2025).

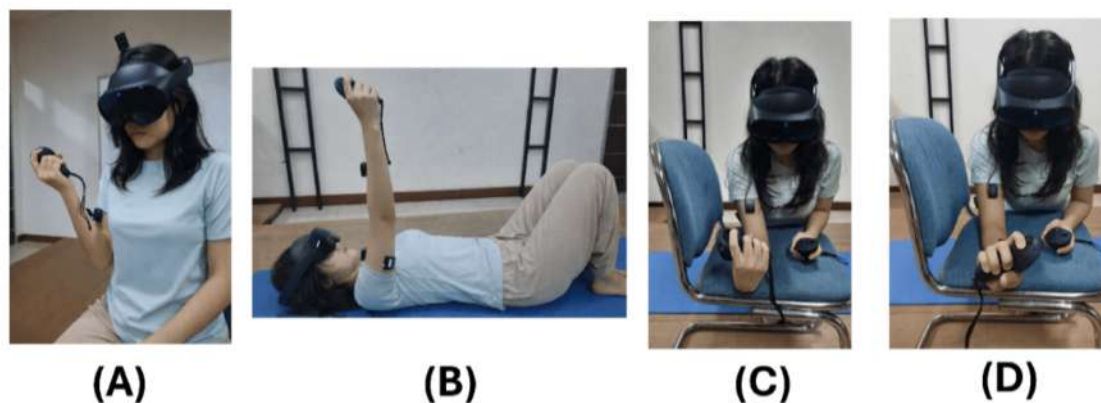


Figure 4 VR-based training. (A) Biceps curl. (B) Lying triceps extension. (C) Wrist flexion curl. (D) Wrist extension curl

Perceived exertion was included as a subjective outcome measure of the effort or fatigue experienced by the participants during the training tasks. Perceived exertion was assessed using the Borg Category Ratio 10 (CR-10) scale. According to Frasier et al. (2024), the Borg CR-10 scale is suitable for evaluating hand and arm fatigue during repetitive lifting tasks. The perceived exertion was measured during both conventional dumbbell training and VR-based training sessions.

In addition to muscle activity and perceived exertion, presence was assessed as an outcome measure in the VR condition using the Barfield Presence Questionnaire (Baren & IJsselstein, 2004). The study evaluated two presence-related items: a global presence rating and a “being there” rating. The specific items were as follows:

1. *“If your level of presence in the real world is 100 and your level of presence is 1, if you have no presence, rate your level of presence in this virtual world.”*
2. *“How strong was your sense of presence, ‘being there,’ in the virtual environment?”* (rated on a scale of 1–5).

2.6 sEMG data processing

The sEMG signal was pre-processed using a band-pass filter with a frequency range of 20–450 Hz (Fuentes del Toro & Aranda-Ruiz, 2025). The filtered signals were subsequently full-wave rectified to standardize signal polarity. Muscle activity was quantified using the root mean square (RMS) method with a moving window approach (window length: 0.01 s; window overlap: 0.005 s). The resulting RMS values were then normalized to the maximal voluntary contraction (MVC) and expressed as a percentage of MVC (%MVC).

2.7 Statistical analysis of the data

Statistical analyses were performed using RStudio (version 4.4.1). Extreme outliers were initially screened using the interquartile range (IQR) method. One extreme value was identified in the global presence rating; therefore, sensitivity analyses were conducted using three scenarios: complete dataset, extreme value exclusion, and winsorization to the IQR-based boundary. All participants were retained in the primary analyses because the statistical conclusions were unchanged across scenarios. Assumption testing included outlier inspection, Shapiro–Wilk normality test, Levene’s and Fligner–Killeen tests for variance homogeneity, and Mauchly’s test of

sphericity. The Greenhouse–Geisser correction was applied when sphericity was violated. For the linear mixed effects models, residual normality was assessed using the Shapiro–Wilk test applied to model residuals, and homoscedasticity was evaluated using residual versus fitted plots. No substantial violations were detected.

Hypothesis 1 was examined using two-way repeated-measures analysis of variance to evaluate the effects of training mode and load level on muscle activity and perceived exertion. Conventional dumbbell exercise and VR-based exergame training were compared across three haptic levels: Haptic Level 1 (250 Hz, 10%), Haptic Level 2 (240 Hz, 45%), and Haptic Level 3 (230 Hz, 100%). Muscle activity was separately analyzed for the biceps brachii, triceps brachii, flexor carpi radialis, and extensor carpi radialis according to their corresponding movements. Holm-corrected paired post hoc comparisons further examined pairwise differences within each mode and between modes at each haptic level. Additional gradient and between-level change analyses were conducted to compare response progression between training modes.

Hypothesis 2 was examined to assess the effects of VR vibration level on muscle activity, perceived exertion, and presence across 250, 240, and 230 Hz. Muscle activity was analyzed using one-way repeated-measures analysis of variance (ANOVA) for each movement–muscle pair, followed by Holm-corrected paired t-tests when significant. Perceived exertion was analyzed using the Friedman test, followed by Holm-corrected Wilcoxon signed-rank tests when appropriate, with Kendall’s W reported as the effect size. Global presence was analyzed using one-way repeated-measures ANOVA, whereas “being there” presence was analyzed using the Friedman test. Post hoc analyses were performed only after identifying significant main effects.

3. Results

3.1 Hypothesis 1: Comparison between conventional dumbbell training and VR-based training on muscle activity and perceived exertion

Hypothesis 1 examined differences in muscle activity and perceived exertion between conventional dumbbell exercise and VR-based exergames across three dumbbell levels (1, 2, and 3 kg) and three haptic levels: low (250 Hz), moderate (240 Hz), and high (230 Hz). Overall, the dumbbell exercise produced higher and more consistent neuromuscular and perceptual responses than VR. Although muscle activity in VR increased across haptic levels, the response was smaller and less consistent, whereas perceived exertion remained low and showed limited level-dependent changes.

For muscle activity, the two-way repeated-measures ANOVA showed a significant load-level effect across all movement–muscle pairs (Table 1): biceps brachii ($F = 52.88$, $p < 0.001$), triceps brachii ($F = 43.94$, $p < 0.001$), flexor carpi radialis ($F = 34.01$, $p < 0.001$), and extensor carpi radialis ($F = 25.43$, $p < 0.001$). All load levels differed significantly in the dumbbell condition, indicating a clear increase in neuromuscular demand from 1 to 3 kg. In contrast, VR showed fewer significant differences across the haptic levels. Biceps brachii and flexor carpi radialis differed only in comparisons involving 230 Hz, and extensor carpi radialis differed only between 240 and 230 Hz. In contrast, triceps brachii was significant across all comparisons at the VR level. Across haptic levels, dumbbell exercise elicited significantly greater activity than VR, especially for biceps and triceps brachii, indicating that VR haptic stimulation can modulate muscle activity but does not reproduce the magnitude of physical loading activation.

For perceived exertion, load level was also significant across all movements (Table 1): biceps curl ($F = 25.34$, $p < 0.001$), lying triceps extension ($F = 30.61$, $p < 0.001$), wrist curl flexion ($F = 32.91$, $p < 0.001$), and wrist curl extension ($F = 42.93$, $p < 0.001$). Dumbbell exercise showed significant differences across all load levels, whereas VR showed no significant differences between haptic levels after Holm correction. The between-condition differences became more pronounced at moderate and high levels, indicating that the perceived-effort gap between the dumbbell and VR increased as the load level increased.

Table 1 Comparison of muscle activity and perceived exertion across haptic levels between conventional dumbbell exercise and VR-haptic exergame training

(a) Omnibus fixed-effect tests

Outcome		Effect		
		Mode	Level	Mode $\times$ Level
Biceps (%MVC)	brachii	F(1, 8) = 73.41; $p < 0.001$; $\eta_p^2 = 0.902$; 95% CI [0.663, 0.955]	F(1.11, 8.86) = 52.88; $p < 0.001$; $\eta_p^2 = 0.869$; 95% CI [0.592, 0.938] ^a	F(1.26, 10.05) = 38.60; $p < 0.001$; $\eta_p^2 = 0.828$; 95% CI [0.521, 0.916] ^a
Triceps (%MVC)	brachii	F(1, 8) = 22.46; $p = 0.001$; $\eta_p^2 = 0.737$; 95% CI [0.285, 0.881]	F(2, 16) = 43.94; $p < 0.001$; $\eta_p^2 = 0.846$; 95% CI [0.653, 0.914]	F(2, 16) = 20.89; $p < 0.001$; $\eta_p^2 = 0.723$; 95% CI [0.409, 0.845]
Flexor carpi radialis (%MVC)		F(1, 8) = 10.91; $p = 0.011$; $\eta_p^2 = 0.577$; 95% CI [0.058, 0.806]	F(1.05, 8.39) = 34.01; $p < 0.001$; $\eta_p^2 = 0.810$; 95% CI [0.425, 0.912] ^a	F(1.11, 8.90) = 15.55; $p = 0.003$; $\eta_p^2 = 0.660$; 95% CI [0.167, 0.839] ^a
Extensor carpi radialis (%MVC)		F(1, 8) = 9.57; $p = 0.015$; $\eta_p^2 = 0.545$; 95% CI [0.034, 0.791]	F(2, 16) = 25.43; $p < 0.001$; $\eta_p^2 = 0.761$; 95% CI [0.479, 0.866]	F(1.10, 8.82) = 13.84; $p = 0.004$; $\eta_p^2 = 0.634$; 95% CI [0.132, 0.827] ^a
Biceps (Borg CR-10)	brachii	F(1, 8) = 22.02; $p = 0.002$; $\eta_p^2 = 0.734$; 95% CI [0.253, 0.879]	F(2, 16) = 25.34; $p < 0.001$; $\eta_p^2 = 0.760$; 95% CI [0.478, 0.866]	F(2, 16) = 16.49; $p < 0.001$; $\eta_p^2 = 0.673$; 95% CI [0.324, 0.816]
Triceps (Borg CR-10)	brachii	F(1, 8) = 17.98; $p = 0.003$; $\eta_p^2 = 0.692$; 95% CI [0.186, 0.860]	F(2, 16) = 30.61; $p < 0.001$; $\eta_p^2 = 0.793$; 95% CI [0.542, 0.884]	F(2, 16) = 27.69; $p < 0.001$; $\eta_p^2 = 0.776$; 95% CI [0.509, 0.875]
Flexor carpi radialis (Borg CR-10)		F(1, 8) = 11.08; $p = 0.010$; $\eta_p^2 = 0.581$; 95% CI [0.061, 0.808]	F(2, 16) = 32.91; $p < 0.001$; $\eta_p^2 = 0.804$; 95% CI [0.566, 0.891]	F(2, 16) = 6.84; $p = 0.007$; $\eta_p^2 = 0.461$; 95% CI [0.062, 0.685]
Extensor carpi radialis (Borg CR-10)		F(1, 8) = 41.31; $p < 0.001$; $\eta_p^2 = 0.838$; 95% CI [0.480, 0.926]	F(2, 16) = 42.94; $p < 0.001$; $\eta_p^2 = 0.843$; 95% CI [0.646, 0.913]	F(2, 16) = 17.36; $p < 0.001$; $\eta_p^2 = 0.685$; 95% CI [0.343, 0.822]

(b) Between-mode pairwise comparisons at each level

Outcome	Load level	Dumbbell, Mean $\pm$ SD	Haptic level	VR-haptic, Mean $\pm$ SD	Mean diff.	95% CI [low, up]	p (Holm)
Biceps brachii (%MVC)	1 kg	6.84 $\pm$ 1.67	250 Hz	4.43 $\pm$ 1.58	2.41	[0.86, 3.96]	0.007 (0.049)
	2 kg	11.66 $\pm$ 2.17	240 Hz	5.51 $\pm$ 2.43	6.16	[4.09, 8.22]	<0.001 (<0.001)
	3 kg	20.27 $\pm$ 5.27	230 Hz	7.89 $\pm$ 3.93	12.38	[9.07, 15.69]	<0.001 (<0.001)
Triceps brachii (%MVC)	1 kg	10.84 $\pm$ 5.09	250 Hz	6.56 $\pm$ 2.32	4.27	[0.87, 7.67]	0.020 (0.079)
	2 kg	22.69 $\pm$ 12.15	240 Hz	8.20 $\pm$ 3.31	14.49	[6.34, 22.63]	0.007 (0.049)
	3 kg	34.40 $\pm$ 14.58	230 Hz	11.21 $\pm$ 4.22	23.19	[12.91, 33.48]	0.003 (0.026)
Flexor carpi radialis (%MVC)	1 kg	6.65 $\pm$ 3.13	250 Hz	4.02 $\pm$ 2.09	2.63	[-0.06, 5.32]	0.055 (0.166)
	2 kg	12.11 $\pm$ 6.28	240 Hz	4.70 $\pm$ 2.75	7.41	[2.30, 12.52]	0.022 (0.086)
	3 kg	19.15 $\pm$ 9.25	230 Hz	7.00 $\pm$ 4.59	12.14	[4.27, 20.02]	0.022 (0.086)
Extensor carpi radialis (%MVC)	1 kg	8.24 $\pm$ 3.65	250 Hz	6.94 $\pm$ 4.01	1.31	[-2.36, 4.97]	0.436 (0.436)
	2 kg	14.85 $\pm$ 8.54	240 Hz	8.19 $\pm$ 4.32	6.67	[0.91, 12.43]	0.057 (0.166)
	3 kg	28.37 $\pm$ 15.09	230 Hz	11.08 $\pm$ 6.31	17.28	[6.22, 28.35]	0.021 (0.086)
Biceps brachii (Borg CR-10)	1 kg	2.69 $\pm$ 1.06	250 Hz	1.48 $\pm$ 1.37	1.20	[0.10, 2.31]	0.036 (0.216)
	2 kg	4.04 $\pm$ 1.34	240 Hz	1.80 $\pm$ 1.31	2.24	[0.77, 3.71]	0.008 (0.088)
	3 kg	6.19 $\pm$ 1.70	230 Hz	2.09 $\pm$ 1.35	4.09	[2.65, 5.53]	<0.001 (0.002)
Triceps brachii (Borg CR-10)	1 kg	3.39 $\pm$ 1.53	250 Hz	2.78 $\pm$ 1.87	0.61	[-1.03, 2.25]	0.417 (0.834)
	2 kg	5.39 $\pm$ 1.71	240 Hz	2.93 $\pm$ 1.73	2.46	[1.34, 3.59]	0.002 (0.022)
	3 kg	8.17 $\pm$ 1.22	230 Hz	3.48 $\pm$ 1.24	4.69	[3.60, 5.78]	<0.001 (<0.001)
Flexor carpi radialis (Borg CR-10)	1 kg	2.22 $\pm$ 1.10	250 Hz	1.50 $\pm$ 0.81	0.72	[-0.16, 1.61]	0.099 (0.397)
	2 kg	3.52 $\pm$ 1.37	240 Hz	2.44 $\pm$ 1.65	1.07	[-0.24, 2.39]	0.100 (0.397)
	3 kg	4.96 $\pm$ 1.62	230 Hz	2.24 $\pm$ 1.50	2.72	[1.36, 4.09]	0.003 (0.028)
Extensor carpi radialis (Borg CR-10)	1 kg	2.57 $\pm$ 0.91	250 Hz	2.00 $\pm$ 1.24	0.57	[-0.44, 1.59]	0.235 (0.705)
	2 kg	4.44 $\pm$ 1.20	240 Hz	2.35 $\pm$ 1.43	2.09	[0.80, 3.38]	0.006 (0.058)
	3 kg	6.91 $\pm$ 1.21	230 Hz	2.24 $\pm$ 1.52	4.67	[3.56, 5.78]	<0.001 (<0.001)

Note. η_p^2 = partial eta squared; CI = confidence interval. ^a Greenhouse–Geisser corrected degrees of freedom and p-value.

The response-gradient analysis further confirmed this pattern. The dumbbell exercise

showed steeper increases in both muscle activity and perceived exertion than VR. For example, the biceps brachii activity increased from 0.07 to 0.20 in the dumbbell condition, but only from 0.04 to 0.08 in the VR condition. Similarly, perceived exertion during biceps curls increased from 2.69 to 6.19 during dumbbell exercise, compared with 1.48 to 2.09 during VR. Overall, dumbbell exercise produced clearer load-dependent neuromuscular and perceptual responses, whereas VR-based exergames elicited a more gradual and limited response pattern. The comparative heatmap visually reinforces this pattern, which shows a stronger activation gradient in the dumbbell condition than in the VR-haptic condition (Figure 5). Activation increased more clearly across all muscles from 1 to 3 kg during dumbbell exercise, whereas VR-haptic stimulation showed a weaker, more compressed activation profile at 250, 240, and 230 Hz.

3.2 Hypothesis 2: Muscle activity, perceived exertion, and presence responses during VR-based training

Hypothesis 2 examined the effect of vibration level on muscle activity, perceived exertion, and presence within the VR-based exergame condition. Three haptic levels were compared: 250, 240, and 230 Hz. Overall, the vibration level significantly modulated muscle activity across all movement–muscle pairs but had limited effects on perceived exertion and presence.

For muscle activity, one-way repeated-measures ANOVA showed significant effects of vibration level for biceps brachii during biceps curl, $F(2,16) = 8.57$, $p_{GG} = 0.014$, $ges = 0.228$; triceps brachii during lying triceps extension, $F(2,16) = 34.68$, $p_{GG} < 0.001$, $ges = 0.268$; flexor carpi radialis during wrist curl flexion, $F(2,16) = 8.05$, $p_{GG} = 0.016$, $ges = 0.143$; and extensor carpi radialis during wrist curl extension, $F(2,16) = 4.52$, $p = 0.028$, $ges = 0.120$. Post hoc tests indicated that significant differences generally involved 230 Hz, except for triceps brachii, which showed significant differences across all pairwise comparisons. This suggests that the triceps brachii was the most responsive muscle to changes in the VR haptic vibration level.

For perceived exertion, Friedman tests showed a significant overall effect only during biceps curl ($\chi^2(2) = 9.52$, $p = 0.009$, $W = 0.529$); however, no significant pairwise differences were found in post hoc Wilcoxon tests with Holm correction. No significant effects were observed for lying triceps extension ($\chi^2(2) = 5.64$, $p = 0.060$, $W = 0.313$), wrist curl flexion ($\chi^2(2) = 5.10$, $p = 0.078$, $W = 0.283$), or wrist curl extension ($\chi^2(2) = 2.08$, $p = 0.354$, $W = 0.115$). These results indicate that vibration-level changes were insufficient to produce consistent differences in perceived exertion across movements.

The presence also remained stable across vibration levels. Global presence ratings did not differ significantly across the frequencies of 250, 240, and 230 Hz ($F(2,16) = 0.817$, $p = 0.459$, $ges = 0.002$), and the “being there” rating also showed no significant effect ($\chi^2(2) = 2.33$, $p = 0.311$, $W = 0.130$). Thus, although the vibration level modulated acute muscle activity, particularly in the triceps brachii, it did not significantly alter perceived exertion or presence within the VR-based exergame condition.

3.3 Linear mixed-effect models

Linear mixed-effects models were additionally fitted to analyze muscle activity (%MVC) while accounting for the data’s repeated-measures structure. Separate models were fitted for each muscle–movement pair. The training mode, haptic level, and their interaction were included as fixed effects, whereas the participant was included as a random intercept. The model was specified as shown in Equation (3):

$$Y_{ijk} = \beta_0 + \alpha_i + \gamma_j + (\alpha\gamma)_{ij} + b_k + \varepsilon_{ijk} \quad (3)$$

where Y_{ijk} represents normalized muscle activity (%MVC) for training mode i , haptic level j , and participant k . Here, α_i represents the fixed effect of training mode, γ_j represents the fixed effect of haptic level, and $(\alpha\gamma)_{ij}$ represents their interaction. The participant-specific random intercept b_k accounts for repeated measurements within each participant, while ε_{ijk} represents

residual error. The fixed effects were tested using Type III tests with Satterthwaite degrees-of-freedom approximation.

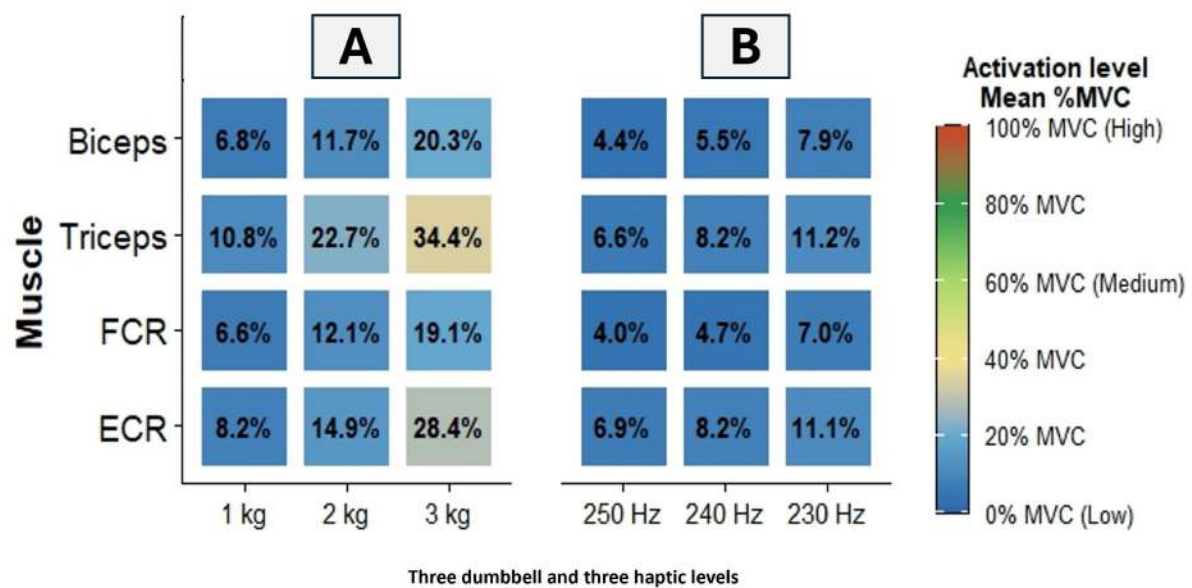


Figure 5 Comparison of the heatmap of mean muscle activation: (a) dumbbell training and (b) VR-haptic training

As shown in Table 2, the training mode, haptic level, and their interaction were significant for all muscle–movement pairs. The significant interaction indicates that the level-dependent change in %MVC differed between conventional dumbbell exercise and VR-haptic training. Therefore, the effect of the haptic level should be interpreted in relation to the training mode.

Table 2 Mixed-effects fixed-effect tests for muscle activity (%MVC)

Muscle	Effect		
	Mode	Level	Mode × Level
Biceps brachii	$F(1,40) = 120.16$; ($p < 0.001$); $\eta_p^2 = 0.75$; 95% CI [0.606, 0.831]	$F(2,40) = 60.37$; ($p < 0.001$); $\eta_p^2 = 0.751$; 95% CI [0.603, 0.831]	$F(2,40) = 20.84$; ($p < 0.001$); $\eta_p^2 = 0.510$; 95% CI [0.276, 0.658]
Triceps brachii	$F(1,40) = 67.04$; ($p < 0.001$); $\eta_p^2 = 0.626$; 95% CI [0.43, 0.745]	$F(2,40) = 22.74$; ($p < 0.001$); $\eta_p^2 = 0.532$; 95% CI [0.302, 0.675]	$F(2,40) = 10.24$; ($p < 0.001$); $\eta_p^2 = 0.339$; 95% CI [0.103, 0.522]
Flexor carpi radialis	$F(1,40) = 38.10$; ($p < 0.001$); $\eta_p^2 = 0.488$; 95% CI [0.262, 0.645]	$F(2,40) = 14.12$; ($p < 0.001$); $\eta_p^2 = 0.414$; 95% CI [0.171, 0.584]	$F(2,40) = 5.26$; ($p = 0.009$); $\eta_p^2 = 0.208$; 95% CI [0.016, 0.403]
Extensor carpi radialis	$F(1,40) = 24.24$; ($p < 0.001$); $\eta_p^2 = 0.377$; 95% CI [0.151, 0.560]	$F(2,40) = 17.49$; ($p < 0.001$); $\eta_p^2 = 0.466$; 95% CI [0.226, 0.625]	$F(2,40) = 7.54$; ($p = 0.002$); $\eta_p^2 = 0.274$; 95% CI [0.054, 0.465]

Note. Values represent Type III fixed-effect tests from separate linear mixed-effects models for each muscle–movement pair. Mode comparing dumbbell and VR-haptic training. Level refers to predefined low, moderate, and high haptic levels and does not imply physical equivalence between dumbbell load and haptic stimulation. Mode × Level tests whether the level-dependent change in %MVC differed between training modes. Participants were included as a random intercept, and each model included 54 observations from 9 participants.

4. Discussion

The first hypothesis demonstrated that conventional dumbbell exercise elicited higher muscle activity and perceived exertion than VR-based exergames across most movement-muscle pairs, particularly at moderate and high load levels. Dumbbell exercise produced a clearer level-dependent increase in the amplitude of sEMG and perceived exertion. Conversely, VR-based exercise elicited lower, more gradual muscle activity responses, with perceived exertion remaining relatively low across haptic levels. These findings indicate that the perceptual mapping between controller vibration and physical dumbbell load was insufficient to reproduce the neuromuscular and subjective demands of conventional resistance exercise.

This difference is primarily due to the absence of mechanical loading in VR. External mass creates gravitational and inertial resistance during dumbbell exercise, requiring greater internal joint moments and increased motor unit recruitment, which are reflected in higher sEMG amplitude (Enoka & Duchateau, 2017; McManus et al., 2020; Vigotsky et al., 2018). In contrast, the VR condition provided vibrotactile feedback without equivalent kinesthetic or force feedback; therefore, the virtual object did not impose real mechanical resistance on the arm (Samad et al., 2019). This explains why muscle activation remained lower in VR despite haptic cues. Nekar et al. (2023) reported lower muscle activity during VR-based exergames than during dumbbell exercise and attributed this to the limited ability of haptic feedback to reproduce physical weight.

The gradient analysis further supports this interpretation. The increase in muscle activity from low to high levels was steeper in the dumbbell condition than in the VR condition. For example, the biceps brachii activity increased from 0.07 to 0.20 during dumbbell exercise, but only from 0.04 to 0.08 during VR exercise. Similar patterns were observed in the triceps brachii, flexor carpi radialis, and extensor carpi radialis. Therefore, the difference between dumbbell and VR exercise was not limited to average activation levels but also reflected different load-response gradients. These distinct load-response patterns support the interpretation that controller-based vibration functioned primarily as a sensory cue rather than as a direct substitute for physical resistance.

A muscle-specific response was observed in the triceps brachii, which was significantly different across all VR haptic levels. This may be related to the biomechanics of lying triceps extension, in which elbow extension is the primary movement. The upper arm may allow a more isolated triceps activation in this position. Such movement characteristics may reduce compensatory involvement and make haptic stimulation changes more detectable in the target muscle. This interpretation is consistent with Alves et al. (2018), who showed that shoulder position, contraction phase, and range of motion influence triceps brachii activation. However, even in this more responsive muscle, dumbbell exercise still produced higher activation, confirming that vibrotactile feedback alone did not match the physical loading neuromuscular demand.

The results of perceived exertion showed an even clearer contrast. In the dumbbell condition, perceived exertion increased consistently with physical load, whereas no haptic level produced significant pairwise differences in perceived exertion across movements in the VR condition. Although vibration intensity could modulate muscle activity, it was not consistently perceived as a greater physical effort. Dissociation was most evident in the triceps brachii, where muscle activity increased significantly across haptic levels, but perceived exertion did not. This mismatch may occur because perceived exertion is closely related to central motor command and the conscious sensation of task heaviness, difficulty, or fatigue (de Morree et al., 2012). Without sufficient mechanical demand, vibration intensity changes may not be strong enough to produce stable increases in perceived effort. In addition, VR exercise may shift attention toward visual feedback, sound, scores, and game elements, thereby reducing physical discomfort or fatigue. This attentional dissociation has been reported in exergame studies and may explain lower perceived exertion despite ongoing physical activity (Düking et al., 2018; Moore & Butler, 2024; Rubio-Arias et al., 2024; Stewart et al., 2022).

The second hypothesis showed that haptic level significantly affected muscle activity across

all movement–muscle pairs but had limited effects on perceived exertion and presence. This indicates that the controller-based vibration was not physiologically neutral because changes in vibration frequency and amplitude could modulate muscle activation even in the absence of a real external load. This finding is consistent with previous evidence that vibration parameters can influence neuromuscular activity (Krol et al., 2011; Mildren et al., 2017). Mechanistically, vibrotactile stimulation may increase afferent input through cutaneous mechanoreceptors and proprioceptive pathways, including the muscle spindles. This afferent input may contribute to the tonic vibration reflex and motor unit activation (Cardinale & Erskine, 2008; Souron et al., 2017). High-frequency vibration may also stimulate Pacinian-related afferents, which are sensitive to vibrotactile stimulation within approximately 100–300 Hz and may support neuromuscular responses (Handler & Ginty, 2021; Saal & Bensmaia, 2014).

However, the haptic effect was not uniform across the muscles. The triceps brachii exhibited the clearest level-dependent response. In contrast, the biceps brachii, flexor carpi radialis, and extensor carpi radialis generally showed significant differences only when the highest haptic level was compared. This pattern is consistent with a response threshold, whereby measurable increases in muscle activity emerge only once the haptic stimulus reaches sufficient intensity.

In contrast, perceived exertion did not increase consistently across haptic levels. Only the biceps curl showed a significant overall Friedman test, but the post hoc comparisons were no longer significant after the Holm correction, whereas the other movements showed no significant effect. These results suggest that vibration may be sufficient to modulate acute muscle activity but not strong or stable enough to reproduce effort sensations comparable to physical loading. Indeed, stronger vibration may influence grip force and perceived effort (Bergevin et al., 2023; Halperin & Vigotsky, 2024; Johansson & Flanagan, 2009; Kim et al., 2023). However, the controller-based haptic feedback used in this study appears insufficient to generate a perceived effort equivalent to that of dumbbell resistance.

The presence also remained stable across haptic levels. Neither global presence nor “being there” ratings differed significantly between 250, 240, and 230 Hz, suggesting that small variations in controller vibration were not the main determinants of presence in this VR exercise environment. Presence is likely shaped by broader experiential and sensorimotor factors, including visual realism, task design, interaction quality, embodiment, and engagement continuity (Gibbs et al., 2022; Nanay, 2018). Because these elements were relatively constant across haptic levels, no significant differences in presence were observed. In addition, pausing the game or removing the headset to complete the Barfield presence questionnaire may have disrupted immersion, consistent with the findings of Bruun-Pedersen et al. (2018). Therefore, future VR-haptic rehabilitation systems should emphasize visual–haptic synchronization, interaction realism, and sensorimotor coherence rather than the isolated adjustment of vibration intensity.

The present findings differ from those of Mologne et al. (2022), who reported that VR-based exergames could outperform conventional exercise in improving body composition, cardiometabolic outcomes, strength, power, and endurance. This difference is likely due to the exercise system design. Mologne et al. (2022) integrated VR exercise with cable resistance training, meaning that the VR condition still involved real mechanical resistance. In contrast, the present study relied on a controller-based vibrotactile feedback without force feedback. Therefore, lower muscle activity and perceived exertion in the VR condition are expected because the system did not provide mechanical loading equivalent to dumbbell exercise.

Several limitations should be acknowledged. First, the VR controller provided vibrotactile feedback but not force feedback. Vibrotactile stimulation alone cannot fully reproduce the heaviness, inertia, and mechanical resistance associated with physical objects (Kurzweg et al., 2024; Moosavi et al., 2023; Stellmacher et al., 2022). Perceived equivalent weight, grip force, contact pressure, motion velocity, and visual–proprioceptive mismatch were not directly measured. Therefore, a full psychophysical weight-perception transfer function could not be estimated from this dataset. Second, the visual and game elements were relatively simple, mainly consisting of hand movements, repetitions, sets, scores, and an avatar demonstration, which may have

limited engagement, embodiment, and presence. Third, this study involved only nine healthy participants and used a short-term experimental protocol. Therefore, the findings represent the acute responses observed in a controlled cohort of healthy participants. These findings should not yet be generalized to patients with neurological impairment, to long-term rehabilitation outcomes, to male or mixed-sex populations, or to broader clinical rehabilitation settings. Fourth, the controller actuator and the software-defined frequency and amplitude settings constrained the haptic output. The normalized amplitude values reflected controller-level commands rather than direct physical measurements of actuator displacement, acceleration, or force.

Despite these limitations, this study makes several contributions to the literature. First, it offers an objective evaluation of VR-based strength exercise by integrating sEMG-based muscle activity with perceived exertion and presence outcomes. This is important because many VR exergame studies emphasize enjoyment, engagement, or functional outcomes, whereas studies on objective neuromuscular responses are less frequent. This study provides initial evidence to characterize the extent to which controller-based vibrotactile feedback can and cannot reproduce the neuromuscular demands of physical resistance exercise by directly comparing VR-based exergame exercise with conventional dumbbell exercise across haptic levels. Second, the results show that vibrotactile feedback can still modulate acute muscle activity, particularly in the triceps brachii, suggesting that motor responses in VR do not entirely depend on mechanical force reproduction. Instead, tactile stimulation may provide afferent input that can influence neuromuscular activation through vibration-related sensorimotor mechanisms (Cardinale & Erskine, 2008; Handler & Ginty, 2021; Souron et al., 2017). Third, this study identified a dissociation between objective and subjective responses, in which muscle activity varied across haptic levels while perceived exertion and presence remained relatively stable. From a rehabilitation perspective, this may be useful because VR-based exercise could stimulate motor activity while maintaining lower perceived effort, potentially supporting adherence and willingness to continue training (Düking et al., 2018; Moore & Butler, 2024; Stewart et al., 2022).

These findings indicate that the current VR-haptic system should not be positioned as a direct substitute for conventional resistance exercise. Although the controller vibration modulated muscle activity, the response was weaker, less load-sensitive, and less perceptually salient than the dumbbell exercise. This reflects an engineering gap: vibrotactile feedback provides sensory cues but does not generate external torque, inertia, or progressive mechanical resistance. Therefore, the proposed system is more suitable as a low-load motor activation and engagement tool, particularly for early-stage or fatigue-sensitive users, than as a stand-alone strength-training device. Commercial VR hardware may support broader, lower-cost, and more scalable rehabilitation delivery, including home-based rehabilitation, remote therapist supervision, and digital rehabilitation for aging populations or users with limited access to clinic-based therapy. However, its therapeutic value for strength-oriented training remains limited unless additional mechanisms are integrated, such as pseudo-haptic with control/display manipulation, wearable resistance, elastic elements, or low-cost force-feedback modules. Broader implementation should also consider cost-effectiveness, supervision needs, maintenance, user training burden, safety, and usability. Additional considerations include data privacy, caregiver support, therapist monitoring workflows, and equitable access across diverse patient groups (Chen et al., 2019; Veras et al., 2023).

Future studies should improve the system and validate the findings in broader populations. First, future VR exergames should integrate force feedback or pseudo-haptic techniques to better simulate heaviness and resistance. One promising approach is control/display ratio manipulation, in which virtual object movement is altered relative to actual hand movement to create an illusion of weight or resistance (Argelaguet & Andujar, 2013; Moosavi et al., 2023; Samad et al., 2019; Ujitoko & Ban, 2021). Second, to increase motivation, enjoyment, embodiment, and presence, exergame design should incorporate richer gamification, adaptive task difficulty, interactive feedback, and real-time avatar mirroring (Ling et al., 2017; Schwarz et al., 2021). Third, future studies should involve larger and more diverse healthy cohorts, followed by patient cohorts,

particularly patients with stroke, to examine clinical translation and long-term rehabilitation effects. Fourth, future studies should also conduct a dedicated weight-matching experiment with a larger sample to estimate psychometric, JND, and perceived-weight curves for validating the haptic-weight mapping. Finally, future research should combine sEMG with motion capture, EEG, and cybersickness assessment to provide a more comprehensive evaluation of biomechanical, cortical, and experiential responses during VR-based rehabilitation. Motion capture can quantify range of motion, speed, acceleration, and movement smoothness, whereas EEG can examine cortical activity and neuroplastic mechanisms, as suggested by previous studies on VR rehabilitation (Huang et al., 2024; Long et al., 2023; Song & Lee, 2021). Such multimodal evaluation is particularly relevant for stroke rehabilitation, as recovery depends not only on muscle activation but also on sensorimotor integration and cognitive-motor control (Huber et al., 2022).

5. Conclusions

This study provides preliminary evidence that controller-based vibrotactile feedback modulates acute upper-extremity muscle activity during VR-based exergames but does not fully reproduce the neuromuscular and perceptual demands of conventional dumbbell resistance training. Dumbbell exercise elicited higher muscle activity and perceived exertion across most movement-muscle pairs, particularly at moderate and high loads. Haptic vibration level significantly affected triceps brachii activity but did not consistently alter perceived exertion or presence. This study showed that vibrotactile feedback is physiologically active but insufficient as a mechanical loading substitute, positioning the system as a low-load motor activation and engagement tool for early-stage, fatigue-sensitive, or home-based rehabilitation rather than a stand-alone progressive resistance-training device. Consumer VR hardware offers affordability, portability, and scalability advantages, though clinical value will require sufficient resistance fidelity alongside safety, usability, supervision feasibility, maintenance efficiency, and functional recovery evidence. Overall, these findings constitute proof-of-concept evidence to guide the development of clinically and commercially viable VR-based haptic rehabilitation systems.

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Author Contributions

Elvina Arvingintyas: conceptualization, data curation, formal analysis, investigation, writing, methodology, review. Khoirul Muslim: conceptualization, data curation, formal analysis, methodology, supervision, validation, writing, review.

Conflict of Interest

The authors declare no conflicts of interest.

Declaration of AI

Generative artificial intelligence tools were employed solely for the purpose of language refinement in the preparation of the manuscript. These tools were not utilized for the generation of scientific content, data analysis, or the formulation of conclusions. The authors retain full responsibility for the accuracy and integrity of the work.

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