Characterizing Locomotor Activity and Internal Load in VR-Based Exergames for Post-Musculoskeletal Injury Rehabilitation

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Abstract: This study investigated the use of VR-based exergames in musculoskeletal injury rehabilitation, focusing on locomotor activity and internal load, as well as the influence of involvement, sensory fidelity, and interface quality. Thirty-seven participants (aged 19-53) engaged in five customized VR games designed for rehabilitation. These games included "Weight Transfer," "Military March," "Side Squat," "Progressive March," and "Walking along a Straight Line." Data were collected using HTC Vive Pro hardware and full-body tracking, with the E4 wristband measuring heart rate and movement and the OMNI scale assessing perceived exertion. The Witmer-Singer Presence Questionnaire evaluated user experience. The results revealed significant differences in heart rate, movement, perceived exertion, and exercise intensity across the exergames. "Progressive March" produced the highest heart rate and intensity, while "Side Squat" generated the most movement and exertion. "Weight Transfer" had the lowest values across all metrics. Additionally, higher levels of presence in the VR environment were linked to more physical activity. These findings suggest that this VR-based exergame session effectively meets each rehabilitation phase's needs. Higher Presence in VR enhances user engagement and realism, leading to increased physical activity.

1 INTRODUCTION

Musculoskeletal injuries profoundly impact daily functioning and overall health, affecting around 40% of the U.S. population (NHIS, 2012; Katz, 2015). These impairments, caused by conditions like chronic joint pain, arthritis, and neurological diseases, can significantly disrupt the performance and participation of athletes, whether elite or amateur, in sports activities. Traditional rehabilitation methods, often repetitive and exhausting, can lead to mental health challenges and reduced motivation, which hinders recovery (Elwyn et al., 2012; Putukian, 2016). Therefore, well-designed and engaging rehabilitation programs are essential for restoring function, preventing long-term disabilities, and ensuring sustained recovery.

In this context, virtual reality (VR) is emerging as a promising tool in musculoskeletal rehabilitation. Although evidence supporting its efficacy is currently limited to specific areas like upper limb rehabilitation (Chaplin et al., 2023), VR systems could offer customizable treatment platforms that improve patient engagement, adherence, and rehabilitation outcomes

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(Aderinto et al., 2023). Growing evidence in the literature supports VR's potential to offer immersive, engaging rehabilitation options, improving both performance and health outcomes (Aderinto et al., 2023; Chaplin et al., 2023). However, the relationship between immersion, satisfaction, and adherence in VR-based rehabilitation remains inconsistent, as current data is still limited (Rose et al., 2018).

Immersion in a virtual environment (VE) produces the sensation of ”Presence,” the feeling of being present in the VE (Riva et al., 2003). Presence is key in VR and is considered an indicator of its ”ecological validity,” referring to the potential transfer of skills acquired in the virtual world to the real world. The ultimate goal of exergame-based training is to improve performance using gamified scenarios, suggesting that if a link between presence and performance is established, exergame designers can manipulate presence to maximize participant performance, thus making the practice more long-lasting. This is particularly significant as VR training is increasingly adopted due to cost and time efficiency (Stevens and Kincaid, 2015).

The main objectives of this study were to characterize the locomotor activity and internal load associated with VR-based exergames used in musculoskeletal injury rehabilitation and to examine how different levels of involvement, sensory fidelity, and interface quality influence these factors. The study's hypotheses are as follows: (i) locomotor activity and internal load during the proposed VR-based rehabilitation session align with the exercise guidelines recommended by the American College of Sports Medicine in terms of the intensity characterizing each phase of the session, and (ii) higher presence in VR exergames is associated with higher levels of physical activity.

The results of this study are expected to provide an important understanding of improving musculoskeletal rehabilitation protocols by aligning VR-based exergames with recommended training guidelines. Furthermore, understanding the locomotor activity and internal load in these sessions will help healthcare professionals optimise exercise intensity and progression. Additionally, the positive relationship between higher presence and better performance in VR exergames suggests that immersive environments can increase patient engagement and physical effort, leading to better rehabilitation outcomes. These results have practical value in clinical settings, allowing healthcare professionals to integrate tailored and engaging VR exergaming sessions into rehabilitation programs for more effective injury recovery.

2 METHODS

2.1 Participants

This study included 37 participants (18 males) aged between 19 and 53 years (M = 23.69; SD = 6.98), recruited from an academic institute. The participants were students enrolled in various engineering, tourism, physical education, and sports programs. Inclusion criteria were: (1) students aged 18 years or older from the academic institute and (2) voluntary willingness to participate. The only exclusion criterion was the presence of any medical contraindications to sub-maximal exercise, as per the guidelines of the American College of Sports Medicine (ACSM, 2022). All procedures were approved by the Faculty of Human Kinetics Ethics Committee, CEIFMH No. 39/2021. The study adhered to the Declaration of Helsinki, and informed consent was obtained from all participants.

2.2 Virtual Reality Gaming Development

Five customized VR games – 'Weight Transfer', 'Military March', 'Side Squat', 'Progressive March', and 'Walking along a Straight Line' – were developed to facilitate a complete rehabilitation session for people recovering from musculoskeletal injuries. All participants followed the same order of games during the session, aiming to include in the training session a warm-up and cool-down, stretching exercises, and a gradual progression of the session's volume and intensity, as recommended. The creation of these VR games involved exploratory research, including open interviews with physiotherapists. The session was set within a soccer-themed environment, incorporating specific soccer elements and gamification techniques to maintain user engagement. Each VR game was designed to address key training domains, such as aerobic endurance, upper and lower body strength, and motor skills. An overview of Exergames, including purposes, scoring, and the functional fitness capacities stimulated, can be found in (Gouveia et al., 2023). The games were developed by two researchers on the topic of computer engineering.

2.3 Software and Hardware

The system integrates HTC Vive Pro hardware, including full-body trackers, and Unity3D software for developing a VR application with full-body tracking. Trackers placed on key body points allow accurate exercise performance monitoring, while inverse kinematics (IK) in Unity calculates joint angles for realistic avatar movement. The VR environment, modeled in Blender as a realistic soccer stadium, enhances immersion, and a customizable avatar increases user engagement. Unity3D's multi-platform capability and SteamVR integration support efficient VR application development across various devices. A detailed description of Software and Hardware can be found in (Gouveia et al., 2023).

2.4 Locomotor Activity and Internal Load

2.4.1 E4 Wristband

The E4 wristband is an advanced device that provides real-time physiological data through four sensors: (1) an electrode for Electrodermal Activity (EDA), (2) a 3-axis accelerometer, (3) a temperature sensor, and (4) a photoplethysmograph (PPG) that measures blood volume pulse (BVP), from which heart rate (HR) and inter-beat interval (IBI) are derived (Empatica, 2022). This study focused on the MEMS-type 3-axis accelerometer, which measures the continuous gravitational force (g) in three spatial dimensions (x, y, and z) and heart rate calculated from the BVP data.

2.4.2 Rate of Perceived Exertion (RPE) Scale

The RPE is a scale that measures the intensity level of physical activity. This study used the OMNI rating of perceived exertion (Robertson et al., 2003). Before the VR game, all participants were individually instructed on the specifics of the OMNI Scale. Then, right after each VR game, the researcher interviewed each participant using the OMNI picture system that elucidated the different levels of effort and the different possible response options (with '0 indicating a minimum response and '10 indicating a maximum response).

2.5 Presence

The Witmer-Singer Presence Questionnaire was used to characterize the experience in the VR games environment (Witmer and Singer, 1998; Witmer et al., 2005). The Presence Questionnaire is a questionnaire that measures the extent to which a user feels present in the virtual experience. It consists of 24 questions divided into four components: involvement, sensory fidelity, adaptation/immersion, and interface quality. This instrument uses a scale of 1 to 7, with one being "Not Convincing" and 7 "Very Convincing".

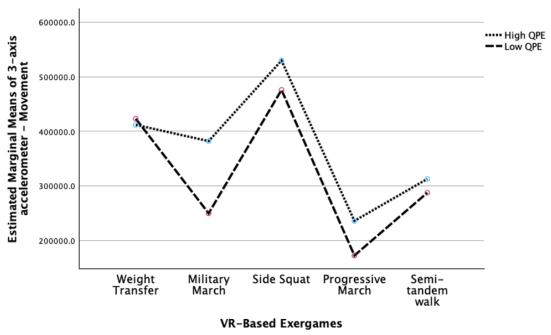

Figure 1: Estimated 3-axis Accelerometer Movement Across Various VR-Based Exergames: A Comparison Between High and Low Presence Levels.

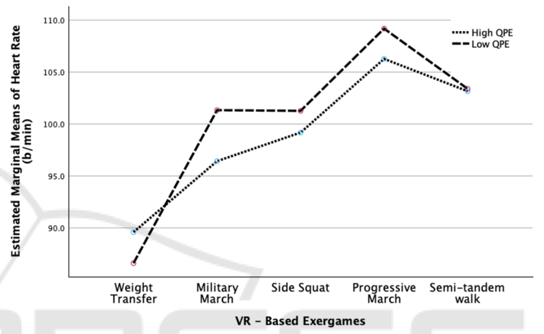

Figure 2: Estimated heart rate Across Various VR-Based Exergames: A Comparison Between High and Low Presence Levels.

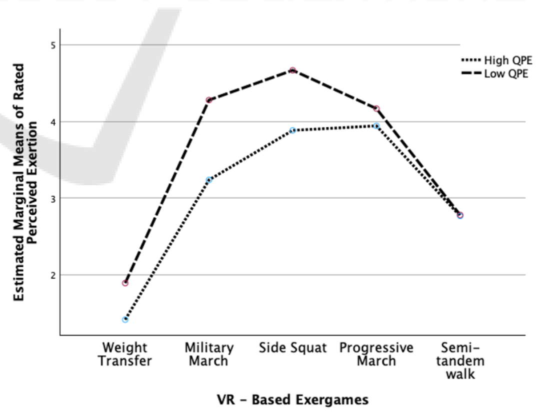

Figure 3: Estimated Rated Perceived Exertion Across Various VR-Based Exergames: A Comparison Between High and Low Presence Levels.

In this study, we considered a high level of presence for all participants who scored above the median (Med = 127).

Table 1: Comparison of Locomotor Activity and Internal Load Across 5 VR-Based Exergames for Post-Musculoskeletal Injury Rehabilitation.

	Weight Transfer (G1)		Military March (G2)		Side Squat (G 3)		Progressive March (G4)		Semi-tandem walk (G5)		p
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
HR (b/min)	88	19.4	98.9	16.1	100.2	17.3	107.7	21.6	103.3	20.3	<.001
Movement (g)	416643	164887	324539	171375	506299	156377	208196	82355	301632	117662	<.001
RPE (n)	1.7	1.3	3.8	1.5	4.3	1.5	4.1	1.6	2.8	1.2	<.001
Intensity (% HR max)	44.9	10.1	50.4	8.1	51.1	8.9	54.9	10.9	52.6	10.3	<.001

3 RESULTS

The results presented in the table demonstrate statistically significant differences across the five VR-based exergames in terms of heart rate (HR), movement (g), rating of perceived exertion (RPE), and exercise intensity (%HR max), with all p-values less than .001. Notably, the Progressive March exergame elicited the highest heart rate (Mean = 107.7 bpm) and exercise intensity (Mean = 54.9% HR max), while the Side Squat resulted in the highest movement (Mean = 506299.2 g) and perceived exertion (Mean RPE = 4.3). Conversely, the Weight Transfer exergame was associated with the lowest heart rate (Mean = 88.0 bpm), perceived exertion (Mean RPE = 1.7), and exercise intensity (Mean = 44.9% HR max), highlighting the variability in physical demands across different exergames.

The exergames had a significant main effect on movement $F(4, 25) = 37.01$, $p < .001$, and a partial eta squared of .856. The comparison of movement across five exergames between high and low levels of presence revealed a significant difference, $F(1, 28) = 4.30$, $p = .047$, partial eta squared = .13, indicating that the high presence group engaged in more physical activity during the analyzed games (Figure 1).

The exergames had a significant main effect on heart rate $F(4, 30) = 6.415$, $p < .001$, and a partial eta squared of .461. The comparison of heart rate across five exergames between high and low levels of presence revealed a non-significant difference, $F(1, 28) = .08$, $p = .78$, partial eta squared = .003, indicating no differences between high presence and low presence during the game (Figure 2).

The exergames had a significant main effect on Rated Perceived Exertion $F(4, 30) = 25.948$, $p < .001$, and a partial eta squared of .776. The comparison of heart rate across five exergames between high and low levels of presence revealed a non-significant difference, $F(1, 33) = 2.10$ $p = .16$, partial eta squared = .06, indicating no differences between high presence and low presence during the game (Figure 3).

4 DISCUSSION

The first purpose of this study was to characterize the locomotor activity and internal load associated with VR-based exergames. We found significant variability in physical demands across different VR-based exergames, with each game setting distinct heart rate, movement, perceived exertion, and exercise intensity levels. "Progressive March," a game focused on aerobic and lower body strength typically included in the conditioning phase of a session, was the most demanding, showing the highest heart rate and exercise intensity, making it practical for cardiovascular improvement, as expected. The "Side Squat" exergame, focused on lower body strength, induced the most movement and perceived effort, indicating strong muscular activation. In contrast, "Weight Transfer," an exergame focused on balance, was the least demanding and suitable for the first phase of a rehabilitation session (warm-up), characterized by light-to-moderate-intensity activity.

The first point to highlight in this study's results is the statistically significant differences in HR, movement (g), RPE, and exercise intensity (%HR max) parameters across the different VR-based exergames. This outcome suggests that each exergame imposes varying levels of physical demand, which aligns with expectations for a Post-Musculoskeletal Injury Rehabilitation training session. In this context, the design of this session is considered a typical single exercise training session, which generally consists of the following phases: (i) Warm-up/Initiation, (ii) Conditioning, and (iii) Cool-down (ACSM, 2022). The warm-up or initiation phase serves as a transitional stage that allows the body to adapt to the exercise session's changing physiological, biomechanical, and bioenergetic demands. It should include light-to-moderate intensity activities, specifically targeting the muscle groups that will be engaged during exercise (McGowan et al., 2015; Garber et al., 2011). During the conditioning phase, training exercises can include aerobic, resistance, flexibility, or sports activities, depending on the specific goals of the session (ACSM, 2022). Finally, the cool-down phase allows the body to return to near-resting levels. Low-to-moderate intensity flexibility exercises, such as static stretching, can also be incorporated during this phase to help the body reach a more relaxed physiological state (Behm, 2024).

As shown, the characterization of locomotor activity and the internal load associated with this VR-based exergame session for rehabilitation following musculoskeletal injuries adheres to the exercise training session components suggested by the American College of Sports Medicine. The ”Weight Transfer” game, which is the first game in the session (i.e., warm-up or initiation phase), was identified as the least demanding exergame, with the lowest heart rate values (88.0 bpm), perceived exertion (RPE = 1.7), and exercise intensity (44.9% HR max), as expected. Additionally, we emphasize the convergence of results between heart rate and exercise intensity for internal load assessment. This result is significant because, in the absence of HR monitors, RPE can be reliably used as a safe and accurate alternative (Borg, 1998). The ”Progressive March” game, corresponding to the conditioning phase, was characterized as the most demanding exergame, producing the highest average heart rate (107.7 bpm) and exercise intensity (54.9% HR max). This game aims to improve cardiovascular fitness and promote greater physiological adaptations. Finally, we highlight the ”Side Squat” game, also part of the conditioning phase, where we observed the highest movement activity and perceived exertion. Once again, we found a convergence between the highest average movement (506299.2 g) (external training load) and the highest perceived exertion (RPE = 4.3) (internal training load). This further validates using RPE as a reliable tool for evaluating exercise intensity (Borg, 1998).

The second aim of this study was to compare the impact of Presence (i.e., involvement, sensory fidelity, adaptation/immersion, and interface quality) on locomotor activity and internal load during the VR experience. As expected, players with higher Presence in the virtual environment engaged in more physical activity, although Presence did not significantly affect heart rate or perceived exertion (internal load). Our study supports the hypothesis that high levels of Presence can enhance user engagement and realism, leading to greater locomotor activity (Luo et al., 2023). Sensory fidelity and interface quality directly influence user immersion, fostering a more natural physical response, which, in turn, elevates exertion levels (Zhang and Song, 2022). These findings are further supported by a study that examined the relationship between presence and performance during a psychomotor task in a virtual environment, suggesting that a higher sense of presence in virtual simulations may positively influence performance and contribute to skill acquisition during virtual training (Stevens and Kincaid, 2015). The relationship between Presence, defined as the sensation of ”being there” in a virtual environment (VE), and its impact on locomotor activity observed in our study aligns with the theory of Presence and Immersion by Ijsselsteijn and Riva (Riva et al., 2003). This supports the idea that greater immersion leads to heightened engagement, as users immersed in the virtual environment are more likely to interact physically and respond naturally to the virtual stimuli.

Some limitations must be acknowledged when interpreting our results. The small and homogeneous sample, which is all students from specific academic programs, restricts the generalizability of the findings to a broader population. Additionally, external factors such as prior experience with VR and varying fitness levels were not controlled, which could influence locomotor activity and internal load. These uncontrolled variables might affect the accuracy of assessing the relationship between Presence and physical engagement in the virtual reality environment. Further research is needed to address these limitations and enhance the study's applicability. These limitations suggest that further research with larger, more diverse samples and greater control over external influences is needed to validate and extend the study's findings. On the other hand, the strengths of this study include the comprehensive characterization of locomotor activity and internal load across various VR-based exergames for rehabilitation. It effectively demonstrates how different exergames impose distinct physical demands, validating the use of RPE as a reliable intensity measurement. Additionally, it explores the impact of Presence on user engagement and physical activity, emphasizing the importance of immersive design for effective rehabilitation

5 CONCLUSSION

The main conclusion is that VR-based exergame sessions present varied physical demands and effectively meet the needs of each rehabilitation session phase. The “Progressive March” promoted cardiovascular fitness, while “Weight Transfer” was the least demanding and appropriate for warm-up. The study also validated the use of the RPE scale as a reliable tool for assessing exercise intensity, particularly when heart rate monitors are unavailable. Additionally, higher levels of presence in the virtual environment correlated with increased locomotor activity, emphasizing the importance of sensory fidelity and immersion for enhancing user engagement and physical responses.

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