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Lower Limb EMG-Based Virtual Reality Interface for Enhanced VR Interaction

Gyounghyun Kim[1], Heejun Youn[2], Seunghyun Lee[3], Soonchul Kwon[*4]

[1]M.S, Department of Smart System, Kwangwoon University, Seoul, South Korea;
[2]M.S, Department of Plasma Bio Display, Kwangwoon University, Seoul, South Korea;
[3]Professor, Ingenium College Liberal Arts, Kwangwoon University, Seoul, South Korea;
*[*4]Associate professor, Graduate School of Smart Convergence, Kwangwoon University, Seoul, South Korea;*
Ehyunkim@kw.ac.kr, hjyun@kw.ac.kr, shlee@kw.ac.kr, [*]ksc0226@kw.ac.kr

Abstract

One of the key elements for maximizing user immersion in virtual reality (VR) is the development of intuitive and sensory interaction methods. While physical devices such as controllers in existing VR equipment are used to control the user's movement intentions, their drawback is that they cannot reflect detailed muscle strength. In this study, we designed a novel interaction method that increases user immersion by reflecting the activity of leg muscles in the VR environment, moving away from the traditional hand-centered control method. In the experiment, surface electromyography (sEMG) was used to measure the muscle activity of the gastrocnemius and tibialis anterior muscles in six participants. Within the VR program, various virtual objects were implemented that responded to the movement and strength of the lower limbs, allowing for a detailed reflection of the user's lower limb movements in the VR environment. The results showed that the interaction method using lower limb muscle activity demonstrated higher user immersion and satisfaction compared to the conventional controller-based method. Additionally, participants reported feeling as if they were using their entire body, greatly enhancing the sense of realism in the VR experience. This study presents a new interaction paradigm utilizing lower limb movements in VR technology and demonstrates its potential for application in various fields such as VR games, rehabilitation training, and sports simulation.

Keywords: *Virtual Reality, Surface Electromyography, User Immersion, User Experience*

1. Introduction

As virtual reality (VR) technology advances, there is a growing interest in various methods to enhance user experience [1,2]. Traditional VR interaction methods have primarily relied on hand controllers or head-mounted display (HMD) movements, which are limited in providing natural full-body interaction and deep immersion [3]. To overcome these limitations, new interaction systems that more precisely detect and reflect users' body movements have recently gained attention [4,5]. VR, recognized as an effective tool in various fields such as gaming, education, and training, provides users with a complete virtual environment and unique immersive qualities. Enhancing immersion in VR environments can lead to improved user experience quality and learning outcomes, prompting the development of various interaction tools and

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Corresponding Author: ksc0226@kw.ac.kr
Tel: +82-2-940-8637, Fax: +82-50-4174-3258
Associate professor Graduate School of Smart Convergence, Kwangwoon University, South Korea

methods [6,7]. In particular, integrating lower limb movements into VR encourages full-body utilization, enabling more natural and intuitive interactions [8]. Electromyography (EMG) technology, which measures and records the electrical activity of muscles, plays a crucial role in accurately detecting users' intentions and movements [9]. Surface EMG (sEMG), in particular, is a non-invasive method that can reflect muscle activity, fatigue, and coordination abilities, making it useful for enhancing the accuracy and personalization of VR interactions [10]. Recent studies have attempted to combine VR and EMG technologies to improve user experience [11]. This study aims to verify the effectiveness of a system that incorporates lower limb muscle activity into VR and explore the potential of integrating EMG technology for lower limb movements in VR experiences. Through this, we aim to increase immersion for VR users, ultimately contributing to expanding the application range of VR technology and improving the quality of user experiences.

2. Background Theory

2.1 Virtual Reality

Virtual Reality (VR) is a technology that provides users with a fully digitalized environment. Figure 1 illustrates the fundamental architecture of VR systems, encompassing technical components, virtual environment interaction, and user experience factors. The key elements of VR are presence and immersion, which enhance user experience and increase effectiveness in various application areas . VR systems support various input methods, with natural user interfaces being crucial for enhanced user experience. For an effective VR experience, it is important to maintain a balance between information content and interaction elements, considering the user's cognitive load. Additionally, accurately tracking and reflecting the user's movements in the virtual environment is key to enhancing immersion [12]. VR technology is being utilized in various fields such as education, training, entertainment, and medicine, and its application range is expanding through continuous technological advancements. Recently, efforts have been made to provide more sophisticated and personalized VR experiences by integrating biometric signal technologies such as EMG [13].

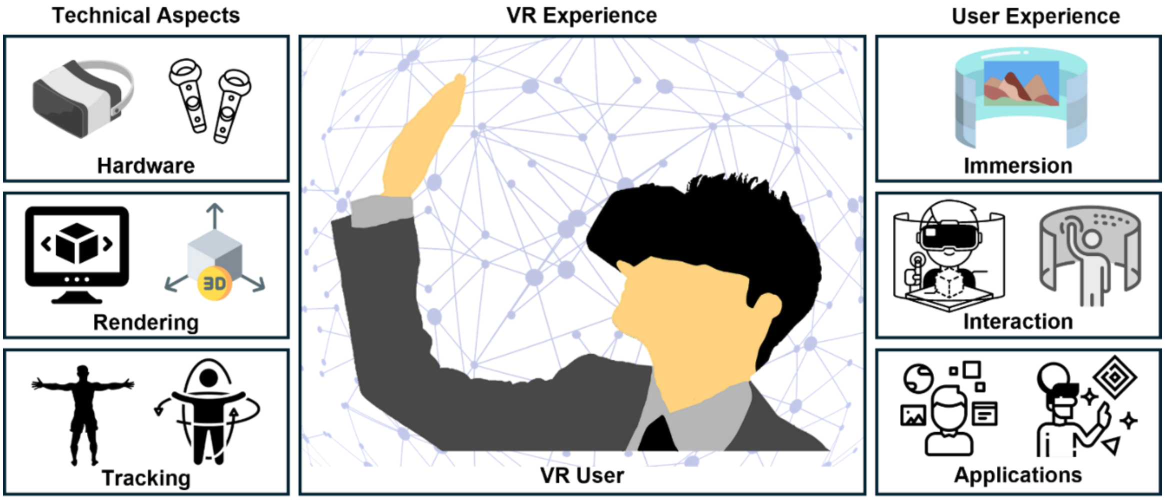


Figure 1. Virtual Reality Architecture

2.2 Electromyography Technology

Electromyography (EMG) is a technique for measuring and analyzing the electrical activity of muscles.

EMG signals capture the electrical changes that occur during muscle fiber contraction, providing information about muscle activation levels, fatigue, and contraction patterns [14]. EMG measurement methods are categorized into invasive needle EMG and non-invasive surface EMG (sEMG). sEMG is widely utilized as it enables real-time data collection through electrodes attached to the skin surface [15]. EMG signals reflect the electrical activity that occurs during muscle contraction and relaxation processes. These signals fluctuate according to the recruitment and firing rate changes of motor units [16]. Through EMG signal analysis, muscle force generation, fatigue, and coordination patterns can be evaluated [17]. This analysis provides crucial information for diagnosing movement disorders, monitoring rehabilitation therapy efficacy, and assessing exercise performance capabilities. The integration of EMG technology in VR-based systems offers several advantages. By detecting and reflecting users' muscle activity in real-time within the virtual environment, more precise and responsive interactions become feasible. Furthermore, it can be employed to dynamically adjust the difficulty of VR content based on muscle activation levels or to objectively evaluate user engagement and immersion. The comprehensive process of EMG signal generation and acquisition, from neural initiation to measurement, is depicted in Figure 2.

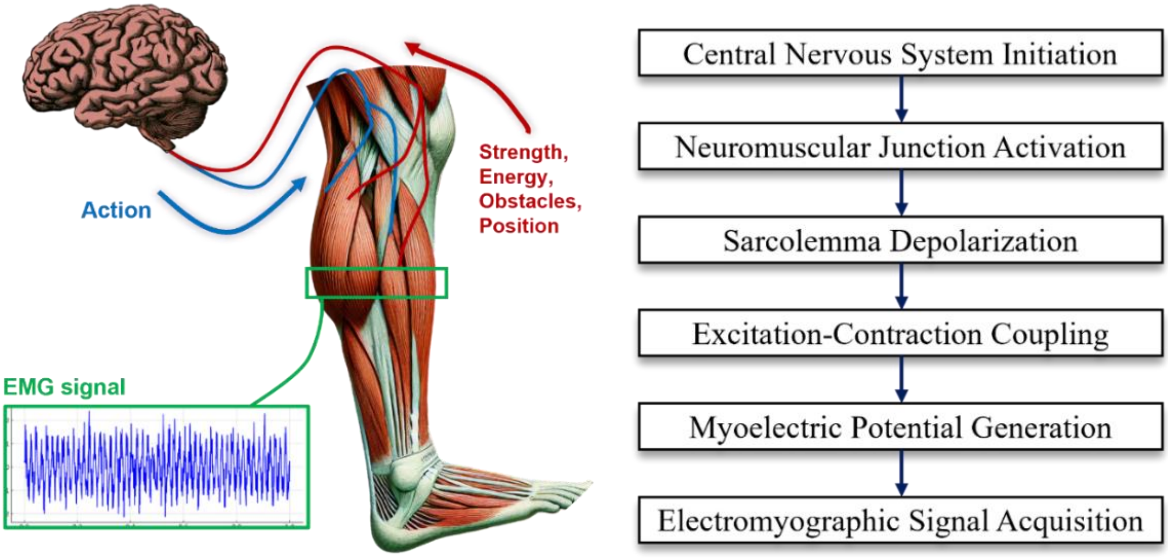


Figure 2. EMG Signal Generation Process

2.3 Related Work

Virtual Reality (VR) and Electromyography (EMG) technologies have shown great potential in the field of human-computer interaction. Kwon et al. emphasized that presence, a key characteristic of VR, induces immersion, which is directly related to improved learning outcomes. Research on the application of VR technology in rehabilitation is also actively progressing. Fukui et al. demonstrated that gait training using virtual reality is effective in improving prosthetic gait symmetry in patients with lower limb amputations [18]. The combination of VR and EMG technologies enables more effective interfaces and rehabilitation systems. Lim et al. proposed a system combining Mixed Reality (MR) and surface EMG (sEMG) technologies, allowing amputees to continue rehabilitation training outside the hospital and enhancing the effectiveness of rehabilitation training by synchronizing intended movements with virtual prostheses in real-time [19]. Palermo et al. improved the user experience of EMG data collection through a system that provides augmented reality-based visual feedback simultaneously with EMG signal measurement [20]. Based on these previous studies, this research proposes a new VR interface that integrates EMG signals. By combining the immersive characteristics of VR with the intuitive control provided by EMG, we aim to provide users with a more natural and effective interaction experience.

3. Experimental Environment

In this study, the Intan RHD 2216 system was used to accurately measure and analyze EMG signals of lower limb movements. This high-performance biosignal measurement equipment can precisely capture subtle EMG signals with high resolution and low noise characteristics. For EMG signal collection, electrodes were attached to the Tibialis anterior and Gastrocnemius muscles. These muscles are optimal for measuring ankle movement and lower limb strength, and the electrodes were placed on the most prominent part of each muscle. For building the Virtual Reality (VR) environment in this study, the Meta Quest Pro headset was used, and the XR scene was developed based on the Unity engine. To accurately track participants' lower limb movements, Vive Trackers were attached to both ankles. These trackers detect the user's foot position and orientation in real-time and reflect them in the XR environment. Interaction events in the XR environment were triggered based on a combination of foot movements detected by the Vive Trackers and normalized EMG signals. This experimental setup enabled effective measurement of Tibialis anterior and Gastrocnemius muscle activity, providing crucial input data for representing lower limb movements and EMG signals in the virtual reality environment.

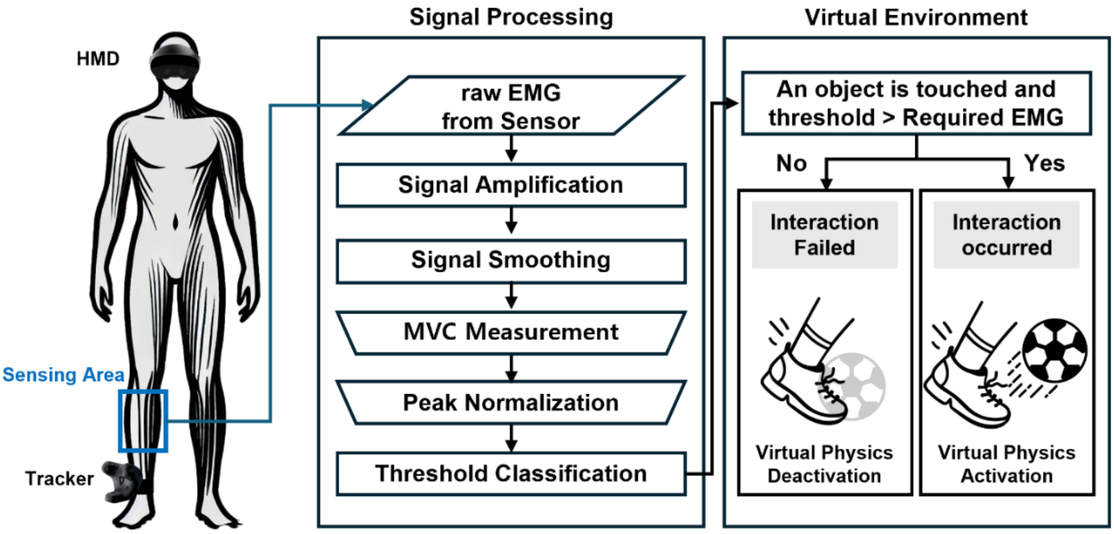


Figure 3. EMG-Based Lower Limb Interaction System for Virtual Reality

The acquired raw signals contain noise and artifacts, making them unsuitable for direct use [21]. Therefore, various techniques were applied in the signal processing stage to refine the signals and process them into a form suitable for analysis. This process includes stages such as amplification and smoothing, each optimized considering the characteristics of the signal. As the first step in signal processing, the signal amplification process enhanced subtle muscle activity to detectable levels. This is particularly important when using low-power wireless EMG sensors, as it compensates for the sensor's limited resolution and improves the signal-to-noise ratio for subsequent processing. Next, a moving average filter was applied to remove high-frequency noise. This filter smooths the signal by calculating the arithmetic mean of adjacent data points. It is particularly effective in removing artifacts caused by irregular skin contact on the amputation surface or external devices. Figure 3 shows the real-time signal acquisition, signal smoothing processing, and signal recording from sensors attached to the tibialis anterior and gastrocnemius muscles.

In the calibration phase of the experiment, participants were asked to contract each muscle with maximum effort k times (10 times in this experiment). The highest EMG value measured during each i-th contraction was set as the i-th Maximum Voluntary Contraction (MVC) value, as shown in equation (1).

$$MVC_i = max(EMG_j), \quad (i = 1,2,\ldots,k), \quad (j = 1,2,\ldots,n-1,n) \tag{1}$$

Next, when calculating the average MVC for normalization using equation (2), the first two and last two of the k MVCs are excluded. This approach aims to obtain a more stable MVC value by excluding initial unstable contractions and potential fatigue effects in the final contractions. Consequently, only the middle six MVC values (assuming k = 10) are used to calculate the average. The equation for calculating the average MVC is as follows:

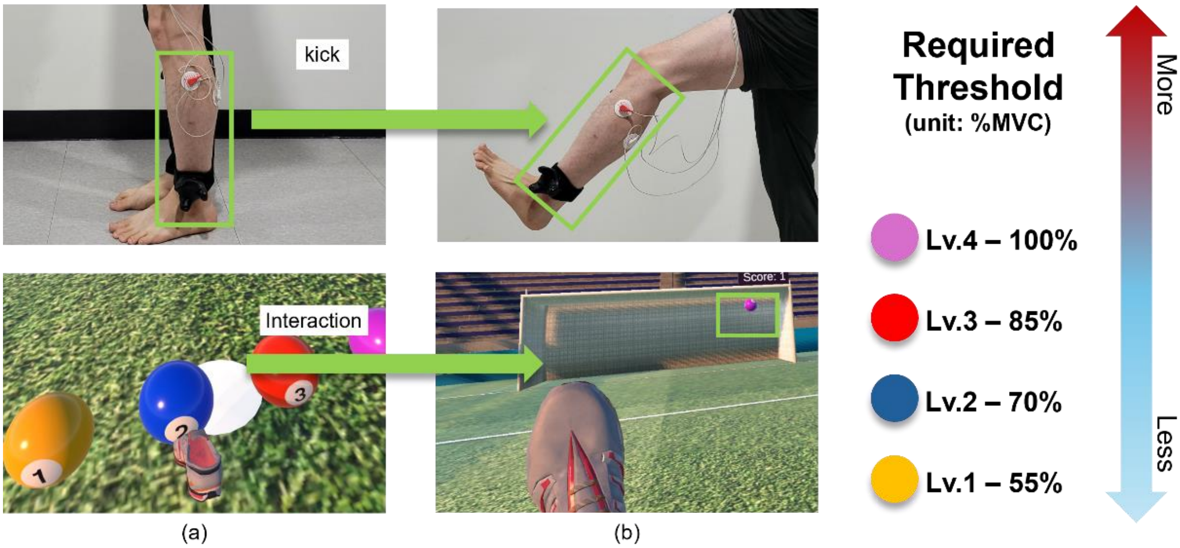
$$mean\ MVC = \frac{1}{k-4}\sum_{i=k-7}^{k-2} MVC_i \tag{2}$$

Finally, normalization was performed to reduce inter-individual and inter-session variability of EMG signals and to obtain a consistent scale [22]. This process converts real-time EMG signals to values between 0 and 100% based on the Maximum Voluntary Contraction (MVC). The normalized EMG values, calculated using equation (3), were derived through min-max normalization, where the average MVC value served as the reference for scaling the smoothed EMG signals. Following data preprocessing, the real-time input of normalized EMG values was utilized to trigger events based on the kicking intensity of objects. The formula used for normalization is as follows:

$$NormalizedEMG_j(\%) = \frac{fEMG_j - min(EMG_j)}{meanMVC - min(EMG_j)} \times 100(\%) \tag{3}$$

The soccer ball kicking scene prepared for this experiment was designed on the premise of tracking foot movements using Vive Trackers. To utilize the Vive Tracker data, the SteamVR SDK was used, and appropriate components were assigned to interactive objects. While the system supports kicking, touching, and pushing interactions with the foot, this study focused primarily on kicking interactions. To set different intensities for the soccer balls, four balls with different threshold levels were created and classified by level to be kicked. These balls were distinguished by color as yellow, blue, red, and purple according to intensity, and were set to have threshold values of 0.55, 0.7, 0.85, and 1.00 respectively, based on normalized EMG. The balls respond when the user makes a kicking motion and the normalized EMG exceeds the ball-specific threshold, visually representing the ball's flight when kicked with sufficient force.

The user's main task is to kick the virtual soccer ball into the designated goal. The user's foot movements and muscle activity detected through the Vive Tracker and EMG sensors are reflected in real-time in the VR environment. Each soccer ball requires different levels of muscle strength according to difficulty, allowing users to objectively understand their lower limb strength levels. For example, level 1 (yellow) soccer balls require low muscle strength, while level 4 (purple) soccer balls require considerable strength. As shown in Figure 4, if the normalized EMG input does not reach the threshold required for each level of virtual ball, the ball remains unresponsive. Physical interaction occurs only when the ball is contacted while the EMG input exceeds the specified threshold.



(a) (b)

Figure 4. Virtual Object event triggering based on EMG-detected muscular activation (a) when kicking a ball lightly, (b) when kicking a ball strongly

4. Experimental Result

This study recruited six participants to validate the system's ability to reflect muscle strength. The participants' average age was 25 years, and none had prior experience with VR systems. This study was conducted on healthy individuals with no musculoskeletal disorders affecting the tibialis anterior and gastrocnemius muscles. All participants were provided with sufficient information about the experiment in advance and voluntarily agreed to participate.

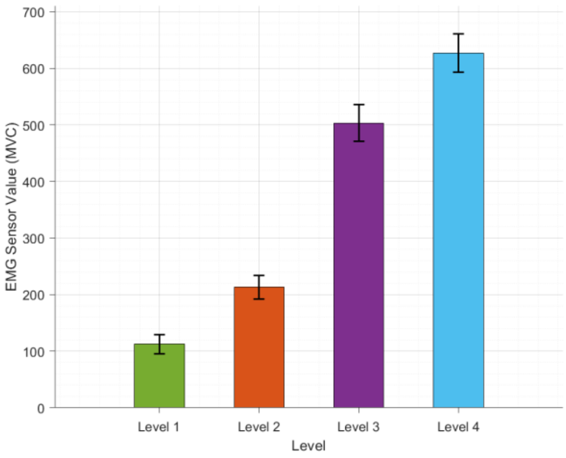


Figure 5. Result of Mean MVC Values and Standard Deviations Across Levels

Quantitative data, including EMG and smoothed signals, were acquired through tests of participants using the proposed system. Figure 5 is a graph showing the average MVC values per level that occurred while participants were kicking soccer balls. This graph shows the mean and standard deviation of the EMG sensor values recorded by participants at each difficulty level. The Y-axis displays EMG sensor values (in MVC units), and the X-axis represents difficulty levels from 1 to 4. In the graph, each bar indicates the average EMG value for that level, and the error bars represent the standard deviation.

Table 1. EMG Values for Different Threshold Levels from six subjects

Threshold Level	Subject 1 (μV)	Subject 2 (μV)	Subject 3 (μV)	Subject 4 (μV)	Subject 5 (μV)	Subject 6 (μV)
Level 1	98	122	89	131	108	127
Level 2	183	217	201	242	209	228
Level 3	452	519	483	537	498	531
Level 4	578	653	599	668	622	641

The EMG sensor values recorded for participants kicking virtual soccer balls at different difficulty levels are presented in Table 1. These results demonstrate a clear correlation between the increasing difficulty of the soccer balls and the higher muscle activation required from participants. Notably, the substantially elevated EMG values observed at levels 3 and 4 indicate that these levels demanded considerable strength from the participants. The increasing magnitude of error bars across levels suggests that individual differences among participants became more pronounced at higher difficulty levels. This data provides valuable insights for objectively evaluating participants' lower limb strength levels and designing personalized VR interactions. Furthermore, it illustrates that a soccer ball kicking game in a VR environment can effectively elicit interactions using various intensities of lower limb strength.

The distinct differences in EMG values between each difficulty level indicate that this system is suitable for accurate muscle strength level discrimination and gradual adjustment of VR interaction intensity. These findings demonstrate that a lower limb EMG-based VR interface can accurately interpret and reflect users' intentions and movements, potentially enhancing the immersiveness and sophistication of the VR experience.

5. Conclusion

In this study, we developed a lower limb electromyography (EMG) based virtual reality (VR) interface and implemented enhanced VR interactions through it. This system measured participants' lower limb muscle activity and movements in real-time, directly reflecting them in the VR environment, providing a more intuitive and immersive user experience. The results showed a significant correlation between participants' muscle activity and interactions in the VR environment when using the EMG-based VR interface. In particular, clear differences in muscle activity were observed when interacting with virtual objects of varying intensities, suggesting that the system can accurately interpret and reflect user intentions and actions. This interface, implemented through the normalization of EMG signals, provided sensory feedback similar to reality while users performed interactions of varying intensities in the VR environment. This allows for more accurate reflection of user intentions and more realistic interactions compared to existing VR systems.

The results of this study demonstrate that the lower limb EMG-based VR interface has great potential as an effective tool for enhanced VR interactions. This technology is expected to significantly improve user experiences in various VR application areas such as gaming, education, and rehabilitation. Future research should further validate the effectiveness of this interface through long-term studies with larger participant groups. Additionally, it will be important to evaluate the practicality and effectiveness of this technology through actual application cases in various VR applications.

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References

[1] A.M. Al-Ansi, M. Jaboob, A. Garad, and A. Al-Ansi, "Analyzing augmented reality (AR) and virtual reality (VR) recent development in education", Social Sciences & Humanities Open, Vol. 8, No. 1, pp. 100532, 2023.10.
DOI: https://doi.org/10.1016/j.ssaho.2023.100532

[2] L.T. De Paolis, C. Gatto, L. Corchia, and V. De Luca, "Usability, user experience and mental workload in a mobile Augmented Reality application for digital storytelling in cultural heritage" *Virtual Reality*, Vol. 27, No. 2, pp. 1117-1143, 2023.
DOI: https://doi.org/10.1007/s10055-022-00712-9

[3] T. Rose, C.S. Nam, and K.B. Chen, "Immersion of virtual reality for rehabilitation-Review" Applied ergonomics, Vol. 69, pp. 153-161, 2018.
DOI: https://doi.org/10.1016/j.apergo.2018.01.009

[4] S. Pyo, J. Lee, K. Bae, S. Sim, and J. Kim, "Recent progress in flexible tactile sensors for human-interactive systems: from sensors to advanced applications" Advanced Materials, Vol. 33, No. 47, pp. 2005902, 2021.
DOI: https://doi.org/10.1002/adma.202005902

[5] V. Ricotti, B. Kadirvelu, V. Selby, R. Festenstein, E. Mercuri, T. Voit, and A.A. Faisal, "Wearable full-body motion tracking of activities of daily living predicts disease trajectory in Duchenne muscular dystrophy" Nature medicine, Vol. 29, No. 1, pp. 95-103, 2023.
DOI: https://doi.org/10.1038/s41591-022-02045-1

[6] A.M. Al-Ansi, M. Jaboob, A. Garad, and A. Al-Ansi, "Analyzing augmented reality (AR) and virtual reality (VR) recent development in education" Social Sciences & Humanities Open, Vol. 8, No. 1, pp. 100532, 2023.
DOI: https://doi.org/10.1016/j.ssaho.2023.100532

[7] D. Kuťák, P.P. Vázquez, T. Isenberg, M. Krone, M. Baaden, J. Byška, and H. Miao, "State of the art of molecular visualization in immersive virtual environments", Computer Graphics Forum, Vol. 42, No. 6, pp. e14738, September 2023.
DOI: https://doi.org/10.1111/cgf.14738

[8] N. Jiang, T. Liu, Z. Cao, J. Cui, Z. Zhang, Y. Chen, and S. Huang, "Full-body articulated human-object interaction", Proceedings of the IEEE/CVF International Conference on Computer Vision, pp. 9365-9376, 2023.
DOI: https://doi.org/10.1109/iccv51070.2023.00859

[9] A. Al-Jumaily and R.A. Olivares, "Electromyogram (EMG) driven system based virtual reality for prosthetic and rehabilitation devices", Proceedings of the 11th International Conference on Information Integration and Web-based Applications & Services, pp. 582-586, December 2009.
DOI: https://doi.org/10.1145/1806338.1806448

[10] A. Phinyomark, E. Campbell, and E. Scheme, "Surface electromyography (EMG) signal processing, classification, and practical considerations", Biomedical Signal Processing: Advances in Theory, Algorithms and Applications, pp. 3-29, 2020.
DOI: https://doi.org/10.1007/978-981-13-9097-5_1

[11] A.F.T. Ibrahim, V.R. Gannapathy, L.W. Chong, and I.S.M. Isa, "Analysis of electromyography (EMG) signal for human arm muscle: A review", Advanced Computer and Communication Engineering Technology: Proceedings of ICOCOE 2015, pp. 567-575, 2016.
DOI: https://doi.org/10.1007/978-3-319-24584-3_49

[12] V. Šimkovič, V. Zajíček and R. Hajtmanek, "User Tracking in VR Environment", 2019 International Conference on Engineering Technologies and Computer Science (EnT), Moscow, Russia, 2019, pp. 80-84, doi: 10.1109/EnT.2019.00022.
DOI: https://doi.org/10.1109/EnT.2019.00022

[13] N. Albers, B. Hizli, B.L. Scheltinga, E. Meijer, and W.P. Brinkman, "Setting physical activity goals with a virtual coach: vicarious experiences, personalization and acceptance", Journal of medical systems, Vol. 47, No. 1, pp. 15, 2023.
DOI: https://doi.org/10.1007/s10916-022-01899-9

[14] Farfán, Fernando D., Julio C. Politti, and Carmelo J. Felice. "Evaluation of EMG processing techniques using information theory", *Biomedical engineering online* 9 (2010): 1-18.
DOI: https://doi.org/10.1186/1475-925X-9-72

[15] R. Fu, B. Zhang, H. Liang, S. Wang, Y. Wang, and Z. Li, "Gesture recognition of sEMG signal based on GASF-LDA feature enhancement and adaptive ABC optimized SVM", Biomedical Signal Processing and Control, Vol. 85, pp. 105104, 2023.
DOI: https://doi.org/10.1016/j.bspc.2023.105104

[16] Rembold, Christopher M. "Regulation of contraction and relaxation in arterial smooth muscle" *Hypertension* 20.2 (1992): 129-137.2023
DOI: https://doi.org/10.1161/01.HYP.20.2.129

[17] M. Al-Ayyad, H.A. Owida, R. De Fazio, B. Al-Naami, and P. Visconti, "Electromyography monitoring systems in rehabilitation: A review of clinical applications, wearable devices and signal acquisition methodologies", Electronics, Vol. 12, No. 7, pp. 1520, 2023.
DOI: https://doi.org/10.3390/electronics12071520

[18] K. Fukui, N. Maeda, M. Komiya, S. Tsutsumi, K. Harada, S. Kuroda, and Y. Urabe, "Walking Practice Combined with Virtual Reality Contributes to Early Acquisition of Symmetry Prosthetic Walking: An Experimental Study Using Simulated Prosthesis", Symmetry, Vol. 13, No. 12, pp. 2282, December 2021.
DOI: https://doi.org/10.3390/sym13122282

[19] G. Lim, H. Youn, H. Kim, H. Jeong, J. Cho, S. Lee, and S. Kwon, "Impact of Mixed Reality-Based Rehabilitation on Muscle Activity in Lower-Limb Amputees: An EMG Analysis", IEEE Access, Vol. 12, pp. 106415-106431, 2024.
DOI: https://doi.org/10.1109/ACCESS.2024.3436710

[20] F. Palermo, M. Cognolato, I. Eggel, M. Atzori, and H. Müller, "An augmented reality environment to provide visual feedback to amputees during sEMG Data Acquisitions", *Towards Autonomous Robotic Systems: 20th Annual Conference, TAROS 2019, London, UK, July 3–5, 2019, Proceedings, Part II 20*, pp. 3-14, July 2019.
DOI: https://doi.org/10.1007/978-3-030-25332-5_1

[21] A.O. Andrade, S. Nasuto, P. Kyberd, C.M. Sweeney-Reed, and F.R. Van Kanijn, "EMG signal filtering based on empirical mode decomposition", Biomedical Signal Processing and Control, Vol. 1, No. 1, pp. 44-55, 2006.
DOI: https://doi.org/10.1016/j.bspc.2006.03.003

[22] M. Besomi, P.W. Hodges, E.A. Clancy, J. Van Dieën, F. Hug, M. Lowery, and K. Tucker, "Consensus for experimental design in electromyography (CEDE) project: Amplitude normalization matrix", Journal of Electromyography and Kinesiology, Vol. 53, pp. 102438, 2020.
DOI: https://doi.org/10.1016/j.jelekin.2020.102438