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Performance assessment of haptic devices for human–object interaction in virtual environment

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ABSTRACT
The integration of physical and virtual reality is gaining increasing relevance, especially in contexts where the interaction between users and digital environments is essential. Virtual reality (VR) enables the simulation of sensory experiences, opening up new opportunities in fields such as industrial training. The quality of simulations depends on how accurately the virtual world replicates the behavior of real objects and the tactile feedback provided to users. Haptic gloves, which deliver tactile sensations during interaction with virtual objects, are among the most advanced tools in this field. This study focuses on characterizing the feedback parameters of the Senseglove Nova and Nova 2 haptic gloves, with the aim of optimizing the user–environment interaction in virtual reality. The primary objective of this study was to characterize the feedback parameters of Senseglove Nova and Nova 2 in virtual environments, with emphasis on identifying differences in object grasping between real and virtual conditions. In this context, angular data from hand movements in both real and virtual scenarios were analyzed and compared to verify their accuracy and enhance interaction with the virtual environment. The proposed methodology establishes a quantitative framework for evaluating haptic feedback accuracy, offering practical insights for the design of immersive training systems.

Section: RESEARCH PAPER

Keywords: haptic feedback; virtual reality; immersive training; pose calibration; finger joint motion analysis

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1. INTRODUCTION

The integration of virtual reality (VR) in training has significantly transformed immersive learning, allowing for the simulation of complex scenarios in a controlled, safe environment. A crucial element in enhancing user experience is tactile feedback, which enables users to physically feel interactions with virtual objects, making the experience more natural and realistic [1]–[5].

1.1. Related work

Haptic gloves, as a cutting-edge technology, play a vital role in delivering real-time tactile sensations, including forces, vibrations, and resistances, to enrich user interaction with virtual environments [6]. Haptic gloves simulate sensations such as touch, texture, resistance, vibration, and weight, which are essential to accurately reproduce complex motor tasks required in technical maintenance contexts. The technologies underlying these devices build on previous work in signal processing [7], sensor networks [8], and smart materials interaction [9], which support the accurate translation of tactile sensations into virtual environments. These approaches are further supported by recent advancements in data-driven sensing, artificial intelligence, and MEMS-based monitoring systems, which have demonstrated their effectiveness in improving accuracy and reliability in complex measurement and detection scenarios [10]–[15].
Crucial aspects for their usability, such as energy efficiency and wireless communication, have been addressed in work related to inductive power transmission [16]–[19] and remote laboratory systems [20]–[26].

While VR visually immerses users in digital spaces, tactile feedback is equally important to ensure an authentic experience. Haptic gloves, designed to provide tactile sensations such as resistance, vibration, and force, make interactions with virtual objects more tangible, closely mimicking real-world contact [27]. The sensation of manipulating and perceiving the texture or resistance of virtual objects is essential for achieving a highly immersive experience [28]. Without tactile feedback, virtual interaction would feel incomplete, diminishing the overall quality and realism of the simulation.

In certain fields, such as professional training, medicine, and industrial design, where precise interactions are critical, the lack of tactile sensations could significantly hinder performance. Haptic gloves address this issue by offering advanced solutions for delivering direct tactile feedback. These gloves are equipped with sensors and actuators that replicate real-world sensations like pressure and resistance, enhancing user immersion [29]. By detecting hand and finger movements, the gloves translate physical gestures into virtual actions, simultaneously generating corresponding physical responses that engage the sense of touch alongside sight and sound. This combination is essential for creating realistic simulations, especially in delicate or highly precise operations [30]. The integration of haptic technologies with augmented and virtual reality frameworks is also closely related to the development of digital twins and cyber-physical systems, which enhance the realism and interactivity of measurement and training environments [31]–[36].

A critical challenge when using haptic gloves is the calibration of various feedback parameters, such as resistance force, vibration intensity, duration, and localization. Proper calibration ensures that tactile sensations are as realistic as possible, making the virtual interaction nearly indistinguishable from real-world contact [37]. Similar challenges related to measurement accuracy and calibration are widely addressed in metrological applications, including vision-based systems and sensor-driven estimation techniques [38].

For instance, when interacting with a virtual object, the glove must provide the appropriate level of resistance to prevent the user's finger from passing through the object, simulating physical presence. Additionally, feedback localization is crucial, as it ensures that the feedback is applied correctly to different parts of the hand or fingers, matching the user's movements and preventing any disorientation [29]. Optimizing these feedback parameters is vital for effective training, where precision and realistic sensory perception are necessary for skill acquisition [37].

Any discrepancies between physical movements and sensory responses could lead to disorientation, reducing the effectiveness of the training simulation. This is particularly significant in medical or industrial training, where the accuracy of tactile feedback is essential for learning complex and delicate techniques [39]. Several studies have demonstrated the advantages of haptic gloves in specific training contexts. More broadly, extended reality (XR) technologies have been increasingly adopted in educational and training environments, where they contribute to bridging theoretical knowledge and practical skills through immersive and adaptive learning approaches [40], [41].

In [42], a robotic system for automatic fall hazard detection has been developed, incorporating haptic gloves to enhance user interaction during training. In [43], wearable physiological sensors have been used to monitor heat stress, highlighting the importance of tactile feedback in training within hot environments.

Despite the significant benefits haptic gloves offer in immersive training, there are practical challenges to their implementation.

1.2. Objectives

An appropriate experimental methodology was established to characterize the angular behavior of human finger movements during object grasping in both real and virtual environments. The procedure, designed to be applicable to general-purpose haptic systems, enabled the acquisition and comparison of phalangeal joint angles across different object sizes and interaction contexts. This methodology was subsequently validated through experimental testing on commercially available haptic gloves, highlighting its effectiveness in quantifying discrepancies between physical and virtual gestures.

The outcomes of this characterization process were then employed to develop an error compensation strategy, based on the metrological limits identified during testing, with the aim of improving the accuracy and coherence of haptic feedback in immersive virtual environments.

2. PROPOSED METHOD

To address the limitations, the experimental methodology illustrated in Figure 1 was implemented. This methodology combines real-world interactions with virtual environments through advanced data collection and processing techniques. The data processing environment collects and analyses data from both the real and virtual experiences, providing insights into the differences between the two environments when grasping objects.

In details, it consists of the following:

- Real environment: the environment in which real objects are grasped using the haptic gloves;
- Virtual environment: the environment in which virtual objects, reconstructed from real ones while preserving their dimensions, are grasped;
- Data processing environment: the space where signals from the glove sensors are collected and analysed to extract angular parameters.

Senseglove Nova/Nova2 haptic gloves, along with the HTC Vive Tracker 2.0, have been adopted to assess the performance of the method; their use, in fact, enables precise tracking of user movements in the real environment, while ensuring that interactions with virtual objects remain realistic and dimensionally accurate.

Figure 1. Block diagram of the proposed experimental architecture integrating real and virtual environments for haptic feedback assessment.

2.1. Hardware configuration

The proposed solution involves a hardware configuration consisting of the following:

- HTC Vive Pro 2;
- HTC Vive Tracker Pro 2;
- Senseglove Nova / Nova 2 Haptic Gloves.

2.1.1. HTC Vive Pro 2

The HTC Vive Pro 2 is a high-end VR headset that delivers exceptional visual clarity and immersion. Equipped with an OLED display offering a resolution of 2448 x 2448 pixels per eye, it provides stunningly clear images and highly detailed renderings, making virtual environments appear incredibly lifelike. The 120 Hz refresh rate ensures smooth visuals by minimizing motion blur and tearing, offering a responsive and precise VR experience. The headset also features an integrated infrared tracking system that accurately detects the user's head position, reducing latency and ensuring a seamless alignment between real-world and virtual movements. Additionally, the integrated spatial audio allows users to perceive sounds from specific directions within the virtual environment, adding another layer of immersion. These features, combined, make the HTC Vive Pro 2 an ideal choice for those seeking the highest-quality VR experience, whether for professional applications or immersive entertainment.

At the core of the Vive Pro 2's spatial positioning is Lighthouse tracking technology. This system uses Base Stations, which emit laser signals and synchronization pulses to track the position of objects in a room. The process begins when the Base Station emits a "Sync Blink", resetting the timers of all sensors in the room. The Base Station then activates one of the two lasers, scanning along either the X or Y plane. When a sensor detects the laser, it records the timer value, and after scanning, the process is repeated with the second laser along the other plane. While this provides a relative 2D position, to achieve accurate 3D tracking, at least two Base Stations are required. However, the system's update frequency of 60Hz, equating to 30 updates per second, can be insufficient for smooth, real-time simulation. Additionally, technology faces limitations in terms of sensor precision and the risk of occlusion, where objects can block or deflect the laser signals, causing measurement errors.

To address these challenges, Lighthouse integrates Inertial Measurement Units (IMUs), which use accelerometers and gyroscopes to track object movement in space. This increases the update frequency to over 500Hz, offering a much smoother tracking experience. However, IMUs are prone to drift, where sensor errors accumulate over time. This is where the Lighthouse system steps in, every 60Hz, the "Sync Blink" corrects the position data, preventing drift and maintaining high accuracy in the virtual environment. This combination of optical tracking and inertial measurement ensures a reliable and immersive VR experience, even in complex and dynamic environments.

2.1.2. Vive Tracker Pro 2

The Vive Tracker Pro 2 by HTC is a cutting-edge tracking device designed to enhance the integration of physical objects within virtual environments, bridging the gap between the real and the virtual world. Fully compatible with the Lighthouse tracking system, the Vive Tracker Pro 2 utilizes advanced technology to provide 6 degrees of freedom (6DoF), allowing for precise tracking of both the position and rotation of objects to which it is attached. This level of detail is essential in applications that demand high fidelity, such as professional training and immersive simulations, where accurate representation and manipulation of objects are key to the effectiveness of the experience.

One of the standout features of the Vive Tracker Pro 2 is its ability to track objects with high precision, even in complex virtual environments. The precise tracking capability ensures that every movement in the physical world is mirrored in the virtual environment, facilitating realistic interaction that enhances the training experience.

Moreover, the Vive Tracker Pro 2 significantly contributes to immersion in virtual reality. Its ability to track objects in 3D space creates a seamless connection between the user and the virtual environment. Whether it is for simulating machinery, sports equipment, or even surgical instruments, the tracker provides a tactile feedback loop, allowing users to physically engage with the virtual world in a way that was previously not possible. By extending control over physical objects, the tracker helps improve the realism of VR simulations, making them more engaging and effective.

In summary, the Vive Tracker Pro 2 is an indispensable tool for applications requiring accurate object tracking and interaction. By offering precise movement and positioning data, it enhances immersion and realism in VR simulations, making it an essential device in various professional fields where high-fidelity training and simulations are critical.

2.1.3. Senseglove Nova / Nova 2

The Nova haptic gloves are advanced devices designed to provide highly realistic sensory feedback, essential for simulating interactions with virtual objects. Each glove is equipped with a system of sensors and actuators distributed across the hand and fingers, enabling the user to experience sensations of contact and resistance that change based on the virtual objects being interacted with. The Nova 2 model enhances hardware responsiveness and tracking precision over its predecessor, the Nova, further enhancing the user experience.

The sensors distributed across the glove's phalanges collect data on the position and deformation of the fingers, providing high-precision tracking of hand movements. Each finger is equipped with individual sensors, including capacitive sensors, resistive strain sensors, and piezoelectric force sensors, all of which contribute to delivering an accurate and realistic tactile experience. The capacitive sensors measure the distance between phalange components with a resolution of approximately 0.1 mm, detecting even the smallest changes in finger movement. The resistive strain sensors detect the changes in resistance caused by finger flexion, while the piezoelectric force sensors measure the forces exerted on the finger segments, enabling the emulation of precise tactile responses.

The sampling frequency of these sensors is around 1000 Hz, allowing for quick and accurate responses to hand movements. To track joint movements, the gloves use MCP Joints technology (metacarpophalangeal), utilizing optical and infrared sensors to measure the angular position of each digital segment (DIP, PIP, MCP) with a resolution of 0.5 degrees. This provides highly precise tracking of finger movements, contributing to the gloves' ability to offer a realistic and responsive virtual reality experience.

With these advancements, the Nova 2 gloves represent a significant leap in the realism of haptic feedback, enhancing the sense of immersion and enabling users to interact with virtual objects as if they were physically present

2.2. Software configuration

To ensure an accurate comparison between the real world and the virtual environment, a meticulous configuration of the scene in Unity was carried out, faithfully replicating the physical environment. Cylinders were selected as the spatial reference for data acquisition due to their simple geometry, which simplifies the task of locating and tracking finger positions during interaction. This choice was crucial, as cylinders provide standardized objects for comparing measurements between the two environments, enabling precise analysis of finger angular variations relative to a known reference surface, and thus facilitating system calibration.

The process began by measuring the cylinders in the virtual environment to obtain reference dimensions consistent with the simulation. Subsequently, the same cylinders were reproduced and measured in the real world, enabling a direct comparison between the two configurations. This phase was critical to ensure the compatibility of the data collected in both environments, allowing for uniform analysis.

After obtaining the physical measurements, the cylinders were scaled in Unity to precisely match their physical counterparts. Unity's mesh was adjusted to ensure an accurate and consistent visual representation within the experimental context.

For each cylinder, a Cylinder object was created using Unity's 3D primitives in the GameObject section. The generated cylinder had default dimensions (height of 2 units and diameter of 1 unit), which were subsequently modified to align with the experimental specifications.

The cylinders were placed within the scene by adjusting their position, rotation, and scale parameters in the Transform component. This ensured consistent alignment with the physical reference environment.

Unity uses the meter as the standard unit of measurement, so the scale on the X and Z axes was adjusted to correctly represent the real-world diameters of the cylinders. The scaling for each cylinder was set as follows:

- Cylinder with a 3 cm diameter: scale 0.03
- Cylinder with a 5 cm diameter: scale 0.05
- Cylinder with a 7 cm diameter: scale 0.07.

The height of the cylinders along the Y axis was adjusted to maintain the proportional relationship with the physical objects. For precise alignment between real and virtual shapes, a capsule mesh was used. A capsule object was added to the scene, and the Capsule Collider component's radius and height were modified to achieve the desired dimensions. For example, for a capsule with a 5 cm diameter, the radius was set to 0.025. The capsule was then aligned with the corresponding cylinders, ensuring that the dimensions and positions matched. This configuration enabled accurate simulation of collisions and physical interactions.

2.3. Data acquisition and processing

The primary goal of the developed code is to acquire real-time angular data of the fingers from the Senseglove haptic device. The execution flow (see Figure 2) is designed to perform periodic measurements and save the data in a CSV file for subsequent analysis.

Upon program startup, the initialization method executes several operations to configure the environment and prepare for data acquisition:

- Detection of the Hand Tracking component: the first step involves calling the Hand Tracking component, which is essential for accessing finger movement data. If the component is not detected, an error is logged to indicate the issue.
- Creation of the Data Saving path: the code defines the path where the acquired data will be saved, using a persistent directory to ensure that data is securely stored and accessible after the application is closed.
- Generation of the Save file: a CSV file is generated to record the acquired data. A unique file name is created to avoid conflicts with existing files. If a file with the same name already exists, a numerical counter is incremented automatically to ensure uniqueness.
- Writing the CSV file header: the header of the CSV file is written, containing variable names for the finger rotation angles. This allows for accurate interpretation of each column during data analysis.

The data acquisition process is continuous and happens in real-time during the program's execution. The acquisition function is carried out at every frame, consisting of several stages:

- Initial countdown: before starting the measurements, a 5-second countdown is executed to prepare the system and the user. After the countdown, the system is ready to begin data acquisition, which is indicated by a designated status variable.
- Acquisition and angle calculation: tracking data is acquired at regular intervals. For each cycle, the rotation angles of the phalanges of each finger are recorded. The angles are calculated by summing the rotational values for each of the three phalanges of each finger, resulting in a "global angle" that represents the overall movement of the finger.

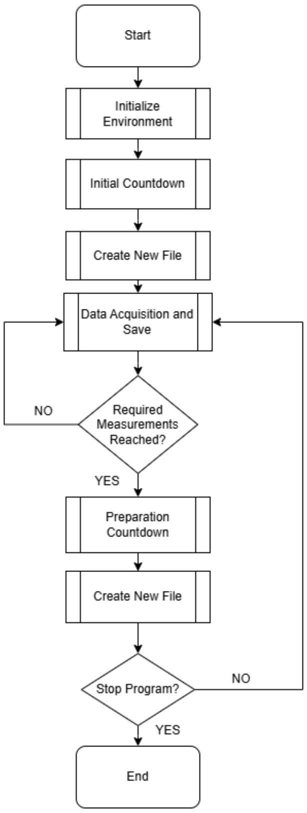

Figure 2. Flowchart of the data acquisition and logging process implemented for real-time measurement of finger joint angles.

- Saving data in the CSV file: after acquiring the global angles of the fingers, the data is written to the CSV file. Each measurement is added as a new row in the file, separated by commas, to maintain a correct tabular format for the data.
- Creation of new files: after 200 measurements have been collected, the system initiates the process of generating a new CSV file. This is done to prevent the creation of excessively large files, which could complicate data management and analysis. A 5-second countdown is used to transition to the new file, which is given a unique name to avoid overwriting existing data.

3. RESULTS

The comparison between the measurements taken in the real world and those in virtual reality was conducted through a detailed analysis of the data collected from the Nova and Nova 2 haptic gloves. The methodology followed a multi-phase approach; each designed to quantify the differences between the two environments and assess the accuracy of hand movement translation into virtual reality.

The first phase involved data collection, during which angular samples were acquired for both test scenarios. It was crucial to gather enough measurements to ensure a meaningful comparison between the gloves' performance in the real world and their response in VR.

Next, an analysis was conducted to examine the differences between the two data sets. For each recorded measurement, the difference between the angular values obtained in the real environment and those acquired in VR was calculated. This step allowed for the estimation of discrepancies between the two environments and an evaluation of how accurately the haptic gloves were able to replicate hand movements in the virtual context.

To gain a more in-depth understanding of the data, descriptive statistics were calculated, including the mean and standard deviation for each measured joint angle. These indicators provided valuable insights into identifying trends or recurring patterns in the discrepancies between real and virtual measurements.

Finally, the results were graphically represented using MATLAB, providing a clear and intuitive visualization of the observed differences. The use of charts made it easier to identify any systematic divergences and facilitated the interpretation of the collected data, thus supporting the overall evaluation of the tracking system's reliability.

One of the most notable issues observed during testing was the inconsistency in the resistance force provided by the glove motors. In certain instances, the motors appeared to lose some of their applied force, or the feedback was less than optimal. This behaviour was linked to variations within the haptic motors themselves, as well as fluctuations in the feedback cycles. The result was often a noticeable instability in the angular data, particularly during movements requiring constant resistance or rapid transitions between hand positions. This variation in force application is a key factor in creating a realistic virtual interaction. In an immersive virtual environment, the tactile feedback provided by the glove is essential to ensure that users feel as though they are truly manipulating objects. Inconsistent feedback undermines this sense of immersion, leading to a less satisfying experience.

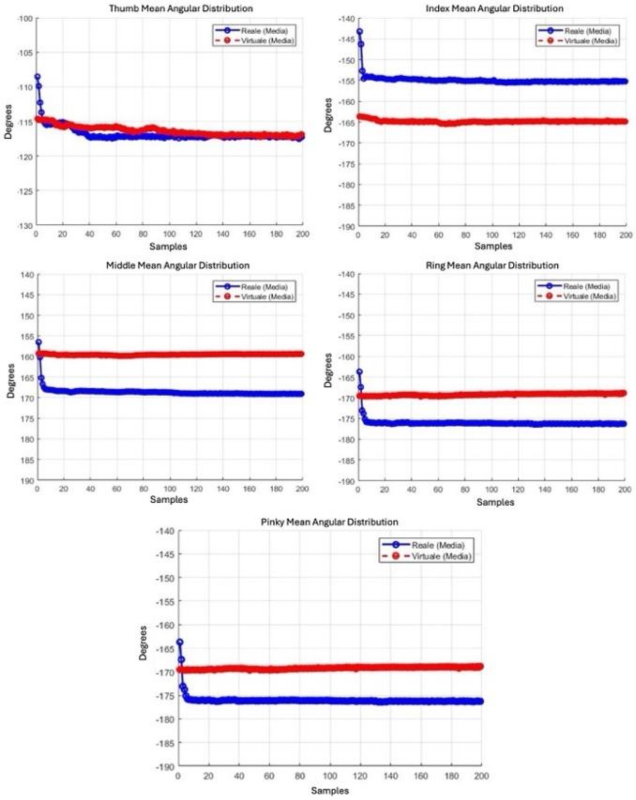

Figure 3. Comparison of measured finger angles in real and virtual environments obtained from the Senseglove Nova during grasping tasks.

The cause of this inconsistency could stem from multiple factors, such as the motor's physical properties, calibration issues, or the software's inability to manage feedback cycles effectively. Addressing these concerns requires improvements in the design of the motors, and the development of more sophisticated algorithms capable of providing smoother, more reliable feedback throughout a wide range of movements. The real challenge lies in maintaining a balance between high-quality, dynamic feedback and consistent resistance force throughout the user's interactions.

Another critical difference concerns the precision of hand tracking in the virtual environment. Accurate tracking is vital for ensuring that the user's hand movements are replicated precisely in the virtual world, contributing to a more immersive and realistic experience. During tests, discrepancies between the tracked positions and actual hand movements were observed, with differences reaching up to 10° in the worst cases. For example, the performance of the Nova glove, as shown in Figure 3, demonstrated noticeable deviations in hand positioning accuracy.

While these discrepancies can be manageable in some scenarios, they are detrimental in highly precise tasks, such as grasping or manipulating objects with fine control. In Table 1 the corresponding values with mean and standard deviation using Nova 1 are shown.

In the case of the Nova 2 glove, however, improvements were made to address this issue. The design of the Nova 2 includes a significant upgrade in the form of an inertial motor incorporated into the thumb mechanism, as shown in Figure 4. This motor allows for a more responsive and dynamic feedback mechanism, enhancing tracking accuracy and enabling better synchronization with hand movements, especially during tasks that demand high tactile precision, such as gripping objects.

Table 1. Angular Differences between real and virtual world using Nova 1.

Finger	Real Mean (deg)	Virtual Mean (deg)	Mean Difference (deg)	Std Dev Difference (deg)
Thumb	-118	-117	1	0.2
Index	-155	-166	11	0.1
Middle	-168	-160	8	0.1
Ring	-176	-170	6	0.1
Pinky	-178	-170	8	0.2

The integration of an inertial motor in the thumb represents a substantial leap forward in glove design. It addresses one of the main limitations observed in the Nova, where the tracking precision suffered due to the lack of a system capable of providing nuanced feedback during thumb movements. The inertial motor provides a more accurate response to hand movements, improving both the tactile feedback and the glove's ability to replicate the physical sensation of interacting with virtual objects. As the technology behind haptic gloves evolves, it becomes increasingly clear that different glove designs require tailored calibration and feedback models. In the case of the Nova 2, the physical and behavioural differences in the thumb motor necessitate a redesign of the system's calibration model. The program logic used for the Nova may no longer suffice, as it fails to account for the unique variables introduced by the inertial motor in the thumb.

For instance, the Nova 2's inertial motor alters the way pressure and force are modulated, which requires the software to adapt to these new variables. In Table 2, the corresponding values with mean and standard deviation using Nova 2 are shown.

A more sophisticated calibration process is needed to ensure that the feedback provided is both precise and responsive to the user's actions. This means adjusting the parameters of the motor's behaviour, ensuring that the force modulation and pressure response align with the user's physical movements.

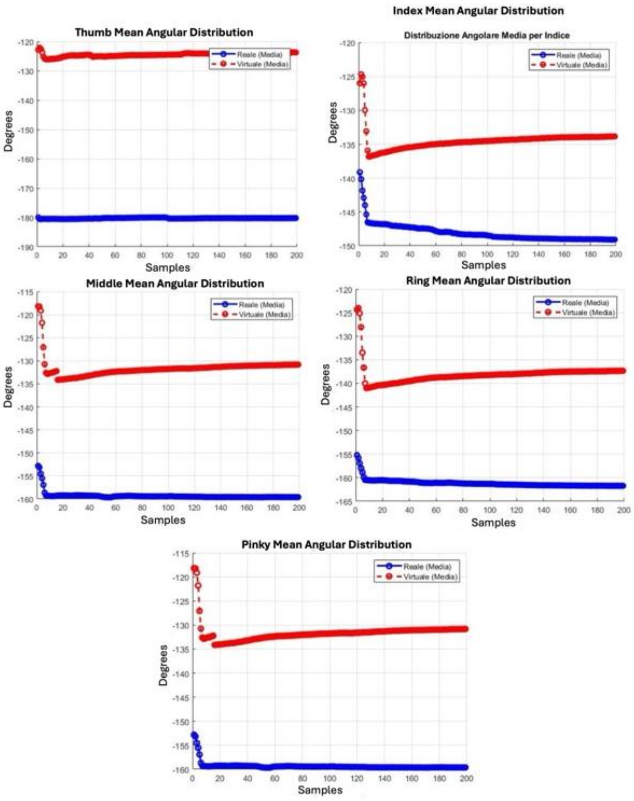

Figure 4. Comparison of measured finger angles in real and virtual environments obtained from the Senseglove Nova 2 during grasping tasks.

Table 2. Angular Differences between real and virtual world using Nova 2.

Finger	Real Mean (deg)	Virtual Mean (deg)	Mean Difference (deg)	Std Dev Difference (deg)
Thumb	-180	-125	55	0.1
Index	-148	-135	13	0.2
Middle	-158	-130	28	0.2
Ring	-162	-138	24	0.1
Pinky	-160	-132	28	0.1

Furthermore, the need for more accurate calibration is not limited to just the thumb motor. A more comprehensive approach that considers the entire glove's performance will allow for more consistent feedback across all fingers, improving the overall tactile experience. The system must account for all aspects of hand movement, from subtle gestures to larger motions, ensuring that each movement is tracked and replicated as accurately as possible.

4. AUTOMATIC POSE CALIBRATION SYSTEM

Following the analysis of the results described in the previous chapter, it emerged that one of the main critical issues in the Nova haptic glove system was the inconsistency of tactile feedback and the low precision in replicating hand movements within the virtual environment. To reduce these errors and improve the fidelity of the simulation, an automatic pose calibration system was developed, designed to dynamically adapt to the physical and kinematic characteristics of each user. This system allows for a personalized sensory experience and ensures more accurate alignment between the real and virtual hand poses during the manipulation of maintenance objects in an immersive environment.

The proposed calibration procedure is based on a user-guided automatic calibration, capable of acquiring and storing the real hand pose of the user while grasping a physical reference object (in this case, a screwdriver). At the end of the procedure, the system records data related to the global finger angles and uses them as reference values for generating the corresponding virtual pose. In this way, each user can interact with the virtual scene, experiencing realistic haptic feedback consistent with their own anatomical hand structure.

4.1. System architecture

The system consists of three main modules, which operate sequentially and cooperate for the calibration and generation of virtual poses (Figure 5):

- User Interface (CountDown Calibrator Manager): manages the entire calibration procedure, providing on-screen messages during runtime. The interface guides the user step by step, ensuring that the pose is recorded correctly and consistently for the object under examination.

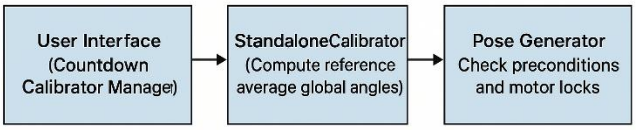

Figure 5. Functional pipeline of the automatic pose calibration system.

- Standalone Calibrator: the script responsible for real-time data acquisition from the haptic gloves during the grasp of the real object. This module calculates the mean global angles for each finger and generates the reference vector, which is then used by the main control system, called Pose Generator.
- Pose Generator: the core of the system, responsible for the control logic during runtime. It uses the reference values obtained during calibration to recognize the user's pose and activate the glove's force actuators when the virtual grasp matches the real one, thus ensuring realistic and stable haptic feedback.

4.2. Operating procedure

During the UI-guided procedure, the user grasps the real object and maintains the grip for a predetermined time, e.g., 10 seconds (Figure 6). During this interval, the Standalone Calibrator script acquires real-time data from the glove sensors and calculates the mean angles of each finger, producing a vector of five values representing the reference poses.

These data are then transmitted to the Pose Generator, which continuously compares the user's current pose with the recorded reference during the execution of the virtual scene. When the absolute difference between the two sets of angles falls within a threshold defined earlier, the system recognizes the grasp and activates the motor locking procedure, simulating the physical resistance of the virtual object.

The introduction of this system has allowed the correction of discrepancies previously observed between real and virtual hand movements. The next paragraph focuses on the Pose Generator script, the heart of the corrections between real and virtual environments.

4.3. Pose Generator

The Pose Generator is the fundamental script for verifying and executing the control logic of the automatic calibration system. Its main task is to check all necessary preconditions and activate the force actuators of the haptic gloves, ensuring realistic feedback during interaction with the virtual object.

The script operates in a cyclic control loop that constantly monitors the glove connection status and the angular position of the fingers. If the device is not properly connected, an error message is displayed to inform the user of the connectivity issue. Once the connection is established, the system continuously reads the joint angles of each finger and calculates the corresponding global angles of all five fingers.

During execution, the Pose Generator continuously compares the hand pose with the one calibrated on the real object. If the angular difference between the two configurations is within a predefined threshold and the motors are idle, it activates the force actuator control. In this way, when the hand enters the valid angular range corresponding to the calibrated pose for that specific tool, a perfect alignment between real and virtual grasp is achieved, enabling immersive and coherent interaction.

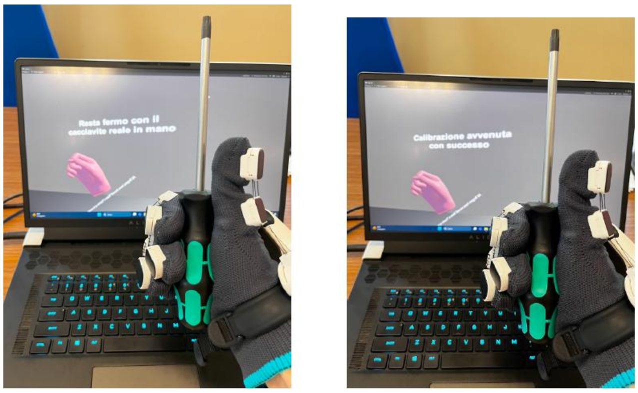

Figure 6. User Interface (UI) for the automatic calibration procedure.

It is also possible to modify the tolerance threshold to adjust recognition sensitivity: a higher value facilitates grasp activation but increases the error between real and simulated poses, whereas a lower threshold increases precision while reducing tolerance.

Gesture recognition is managed by a dedicated function that, at each update cycle, calculates the absolute difference between the instantaneous global angle and the reference angle recorded during calibration. If this difference is below the threshold for all fingers, the function returns a positive value and activates the recognition flag, one of the preconditions necessary for motor locking.

When all conditions are met, the Pose Generator initiates the locking procedure, queuing all commands to be sent to the actuators and setting adjustable force and squeeze levels according to the application. From a visual perspective, the effect is immediately noticeable, as the virtual grasp of the screwdriver closely matches the real one (Figure 7).

5. CONCLUSION

This work has presented an analysis of the phases necessary to manage hand–object poses in virtual environments. Subsequently, the design and implementation of an automatic pose calibration system for the SenseGlove Nova 2 haptic gloves was addressed, aimed at improving the accuracy and realism of hand–object interactions in immersive virtual environments. Thanks to the proposed architecture, which integrates real and virtual environments through precise tracking and real-time data acquisition, it was possible to analyze the correspondence between physical and virtual gestures and identify the main limitations of current haptic feedback systems.

Experimental analysis showed that although the Nova and Nova 2 gloves achieve a high level of accuracy in reproducing finger joint movements and tactile sensations, precision and repeatability remain areas for improvement. Differences between consecutive trials, particularly in resistance force and joint angle

Figure 7. Visual representation of the virtual grasp following the activation of the Pose Generator module.

stability, highlight how significantly motor inconsistencies and calibration sensitivity can affect the overall realism of the experience.

Quantitatively, the system performance was evaluated in terms of key performance parameters, such as accuracy (mean angular error) and precision (standard deviation). Results showed that the mean angular discrepancy between real and virtual poses varies across fingers, ranging approximately from 13° up to 55°, with the largest deviation observed in the thumb. In contrast, precision remains relatively high, with standard deviation values generally below 1° for both real and virtual measurements, indicating stable but systematically biased measurements. These results highlight the presence of a consistent offset between real and virtual representations, suggesting that calibration, rather than random noise, plays a crucial role in reducing systematic errors.

The introduction of the Pose Generator module, in combination with the Standalone Calibrator, effectively addressed some of these critical issues, by implementing an automatic calibration procedure capable of dynamically adapting to the morphology and grasp behavior of each user. This ensured a more consistent alignment between real and virtual poses during object manipulation, especially in maintenance training contexts.

From an industrial training perspective, the proposed system has relevant implications. Improved alignment between real and virtual hand poses enhances task accuracy and reduces the risk of negative training transfer, which is critical in scenarios such as maintenance, assembly, and safety-critical operations. Furthermore, more reliable and realistic haptic feedback can increase user engagement, reduce cognitive load, and support faster skill acquisition, making immersive VR training more effective and scalable in industrial environments.

However, some limitations must be acknowledged. Firstly, the study focuses only on two glove models (Nova and Nova 2), which may limit the generalizability of the results to other haptic devices with different actuation or sensing technologies. Secondly, the experimental evaluation was conducted on a limited sample size, which may not fully capture inter-user variability in hand morphology and interaction strategies. Additionally, external factors such as tracking noise and hardware constraints may have influenced the observed variability in force feedback and joint angle estimation.

Future work will focus on extending the proposed calibration framework to a wider range of haptic devices and interaction scenarios, including more complex manipulation tasks. A larger-scale user study will be conducted to statistically validate the robustness and generalizability of the approach. Moreover, integrating adaptive or learning-based calibration techniques could further improve performance, by continuously refining the calibration parameters during use. Finally, the combination of the proposed system with advanced physics-based interaction models and multimodal feedback could further enhance realism and effectiveness in immersive training applications.

REFERENCES

[1] A. B. Jani, N. A. Kotak, A. K. Roy, Sensor Based Hand Gesture Recognition System for English Alphabets Used in Sign Language of Deaf-Mute People, Proc. of IEEE Sensors, New Delhi, India, 2018, pp. 1–4.
DOI: 10.1109/ICSENS.2018.8589574

[2] D. Scorgie, Z. Feng, D. Paes, F. Parisi, T. W. Yiu, R. Lovreglio, Virtual reality for safety training: A systematic literature review and meta-analysis, Saf. Sci. 171 (2024), 106372.
DOI: 10.1016/j.ssci.2023.106372

[3] P. Strojny, N. Dużmańska-Misiarczyk, Measuring the effectiveness of virtual training: A systematic review, Computers and Education: X Reality 2 (2023), 100006.
DOI: 10.1016/j.cexr.2022.100006

[4] M. Coban, Y. I. Bolat, I. Goksu, The potential of immersive virtual reality to enhance learning: A meta-analysis, Educ. Res. Rev. 36 (2022), 100452.
DOI: 10.1016/j.edurev.2022.100452

[5] N. Tecce, G. de Alteriis, G. de Alteriis, L. Verde, M. F. Tecce, A. Colao, G. Muscogiuri, Harnessing the Synergy of SGLT2 Inhibitors and Continuous Ketone Monitoring (CKM) in Managing Heart Failure among Patients with Type 1 Diabetes, Healthcare (Switzerland) 12 (2024), 753.
DOI: 10.3390/healthcare12070753

[6] R. J. Stone, Haptic feedback: A brief history from telepresence to virtual reality, in: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 2058 (2001), pp. 1–16.
DOI: 10.1007/3-540-44589-7_1

[7] L. Angrisani, F. Bonavolontà, M. D'Apuzzo, R. S. L. Moriello, M. Vadursi, A compressive sampling based method for power measurement of band-pass signals, Proc. of the 2013 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Minneapolis, USA, 06–09 May 2013, pp. 102–107.
DOI: 10.1109/I2MTC.2013.6555390

[8] L. Angrisani, F. Bonavolontà, G. d'Alessandro, M. D'Arco, Inductive power transmission for wireless sensor networks supply, Proc. of the 2014 IEEE Workshop on Environmental, Energy, and Structural Monitoring Systems Proceedings, IEEE, Naples, Italy, 2014. pp. 1–5.
DOI: 10.1109/EESMS.2014.6923289

[9] D. Pierleoni, M. Minelli, G. Scherillo, G. Mensitieri, V. Loianno, F. Bonavolontà, F. Doghieri, Analysis of a Polystyrene-Toluene System through "dynamic" Sorption Tests: Glass Transitions and Retrograde Vitrification, Journal of Physical Chemistry B 121 (2017) 42.
DOI: 10.1021/acs.jpcb.7b08722

[10] G. de Alteriis, D. Ruggiero, F. Del Prete, C. Conte, E. Caputo, V. Bottino, F. Carone Fabiani, D. Accardo, (+ 1 more author), The Use of Artificial Intelligence Approaches for Performance Improvement of Low-Cost Integrated Navigation Systems, Sensors 23 (2023)13, 6127.
DOI: 10.3390/s23136127

[11] G. de Alteriis, G. Mariniello, T. Pastore, A. T. Silvestri, G. Augugliaro, I. Papallo, C. Mennuti, A. Bilotta, (+ 2 more authors), Tendon Anomaly Identification in Prestressed Concrete Beams Based on an Advanced Monitoring MEMS and Data-Driven Detection of Structural Damage, Sensors 25 (2025) 1, 289.
DOI: 10.3390/s25010289

[12] G. de Alteriis, E. Caputo, R. S. Lo Moriello, On the suitability of redundant accelerometers for the implementation of smart oscillation monitoring system: Preliminary assessment, Acta IMEKO 12 (2023) 2, pp. 1–9.
DOI: 10.21014/actaimeko.v12i2.1532

[13] S. Baik, S. Park, J. Park, Haptic Glove Using Tendon-Driven Soft Robotic Mechanism, Front. Bioeng. Biotechnol. 8 (2020).
DOI: 10.3389/fbioe.2020.541105

[14] S. Sunandar, N. D. Rahmawati, A. Wibisono, A. Buchori, VAR based (Virtual Augmented Reality) Education Game Dissemination in Geometry Learning at Unissula Semarang, SSRN Electronic Journal (2021).
DOI: 10.2139/ssrn.3865850

[15] J. Radianti, T. A. Majchrzak, J. Fromm, I. Wohlgenannt, A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda, Comput. Educ. 147 (2020).
DOI: 10.1016/j.compedu.2019.103778

[16] P. Arpaia, F. Bonavolontá, A. Cioffi, Problems of the advanced encryption standard in protecting Internet of Things sensor networks, Measurement, 161 (2020), 107853.
DOI: 10.1016/j.measurement.2020.107853

[17] A. T. Silvestri, G. de Alteriis, E. Cozzolino, R. Schiano Lo Moriello, A. Squillace, A. Astarita, Monitoring system and anomaly detection in dissimilar friction stir lap welding based on MEMS sensor, power consumption, and temperature, Int. Journal of Advanced Manufacturing Technology 139 (2025), pp. 4759–4777.
DOI: 10.1007/s00170-025-16163-w

[18] A. Vitale, F. Lamonaca, Enhancing GeoAI land cover classification via hyperparameter tuning and cross-validation: A case study in Ravenna, Italy, Measurement, 257 A (2026), 118662.
DOI: 10.1016/j.measurement.2025.118662

[19] D. L. Carnì, F. Lamonaca, Automatic Power Quality Events Classifier based on hybrid CNN–LSTM network and multisine fitting algorithm, Measurement, 270 (2026), 120778.
DOI: 10.1016/j.measurement.2026.120778

[20] F. Bonavolontà, M. D'Arco, A. Liccardo, O. Tamburis, Remote laboratory design and implementation as a measurement and automation experiential learning opportunity, IEEE Instrum. Meas. Mag. 22 (2019) 6, pp. 62–67.
DOI: 10.1109/MIM.2019.8917906

[21] L. Angrisani, F. Bonavolontà, M. D'Arco, A. Liccardo, A flexible remote laboratory with programmable device under test, Measurement, 156 (2020), 107584.
DOI: 10.1016/j.measurement.2020.107584

[22] L. Angrisani, P. Arpaia, F. Bonavolonta, R. S. Lo Moriello, Academic FabLabs for industry 4.0: Experience at University of Naples Federico II, IEEE Instrum. Meas. Mag. 21 (2018) 1, pp. 6-13.
DOI: 10.1109/MIM.2018.8278802

[23] A. Liccardo, P. Arpaia, F. Bonavolontà, E. Caputo, F. de Pandi, V. Gallicchio, A. Gloria, R. S. Lo Moriello, An Augmented Reality Approach to Remote Controlling Measurement Instruments for Educational Purposes During Pandemic Restrictions, IEEE Trans. Instrum. Meas. 70 (2021), pp. 1–20.
DOI: 10.1109/TIM.2021.3101314

[24] R. S. Lo Moriello, A. Tocchi, A. Liccardo, F. Bonavolonta, G. de Alteriis, Exploiting IoT-Oriented Technologies for Measurement Networks of Environmental Radiation, IEEE Instrum. Meas. Mag. 23 (2020) 9, pp. 36–42.
DOI: 10.1109/MIM.2020.9289067

[25] A. T. Silvestri, A. El Hassanin, G. de Alteriis, A. Astarita, Energy Consumption and Tool Condition in Friction Stir Processing of Aluminum Alloys, International Journal of Precision Engineering and Manufacturing-Green Technology 12 (2025), pp. 1–18. DOI: 10.1007/s40684-024-00633-9

[26] G. de Alteriis, R. Schiano Lo Moriello, A. Astarita, A. T. Silvestri, A coherence-driven method for instability frequency identification and uncertainty evaluation in friction stir welding, Measurement (Lond). 275 (2026), 121385.
DOI: 10.1016/j.measurement.2026.121385

[27] J. Dong, J. Zhang, X. Ma, P. Ren, Z. C. Qian, Y. V. Chen, Virtual reality training with passive haptic feedback for cryoem sample preparation, Proc. of the 26th IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Osaka, Japan, 2019, pp. 892–893.
DOI: 10.1109/VR.2019.8797918

[28] C. Anitha, P. L. Soundarraj, N. Geethanjali, C. Boopathy, A. N. Venkatesh, I. M. Krishna, Human-Computer Interaction: Innovations and Challenges in Virtual Reality, Proc. of the 9th International Conference on Science, Technology, Engineering and Mathematics: The Role of Emerging Technologies in Digital Transformation, ICONSTEM, Chennai, India, 2024, pp. 1–5.
DOI: 10.1109/ICONSTEM60960.2024.10568875

[29] J. Perret, E. Vander Poorten, Touching virtual reality: A review of haptic gloves, Proc. of ACTUATOR 2018 - 16th Int. Conf. and Exhibition on New Actuators and Drive Systems, 2018.

[30] S. Jadhav, V. Kannanda, B. Kang, M. T. Tolley, J. P. Schulze, Soft robotic glove for kinesthetic haptic feedback in virtual reality environments, Proc. of the IS and T Int. Symp. on Electronic Imaging Science and Technology, 2017, pp. 19–24.
DOI: 10.2352/ISSN.2470-1173.2017.3.ERVR-102

[31] A. Liccardo, F. Bonavolontà, R. S. Lo Moriello, F. Lamonaca, L. De Vito, A. Gloria, E. Caputo, G. de Alteriis, Digital twins based on augmented reality of measurement instruments for the implementation of a cyber-physical system, Acta IMEKO 11 (2022) 4, pp. 1–8.
DOI: 10.21014/actaimeko.v11i4.1397

[32] F. Tao, Q. Qi, L. Wang, A. Y. C. Nee, Digital twins and cyber–physical systems toward smart manufacturing and industry 4.0: Correlation and comparison, Engineering 5 (2019) 4, pp. 653–661.
DOI: 10.1016/j.eng.2019.01.014

[33] F. Bonavolontà, D. L. Carnì, F. de Pandi, F. Lamonaca, A. Liccardo, Reconfigurable measurement setup for laboratory activities in augmented reality, in: Measurement: Sensors 38 (2025), 101321.
DOI: 10.1016/j.measen.2024.101321

[34] A. Liccardo, F. Lamonaca, F. Bonavolonta, An MQTT-Based Interface for Remote Control of GPIB Instruments: Ensuring User Experience in Augmented Reality and Metaverse Laboratories, Proc. of the 2025 IEEE Int. Workshop on Metrology for Living Environment, MetroLivEnv, Venezia, Italy, 2025, pp. 167-171.
DOI: 10.1109/MetroLivEnv64961.2025.11107076

[35] G. de Alteriis, A. T. Silvestri, C. Conte, V. Bottino, E. Caputo, A. Squillace, D. Accardo, R. Schiano Lo Moriello, Innovative Fusion Strategy for MEMS Redundant-IMU Exploiting Custom 3D Components, Sensors 23 (2023) 5.
DOI: 10.3390/s23052508

[36] A. T. Silvestri, S. Amirabdollahian, M. Perini, P. Bosetti, A. Squillace, Direct Laser Deposition for Tailored Structure, in: ESAFORM 2021, 24th International Conference on Material Forming, Liège, Belgium, 2021.
DOI: 10.25518/esaform21.4124

[37] D. Wang, M. Song, A. Naqash, Y. Zheng, W. Xu, Y. Zhang, Toward Whole-Hand Kinesthetic Feedback: A Survey of Force Feedback Gloves, IEEE Trans. Haptics 12 (2019) 2, pp. 189–204.
DOI: 10.1109/TOH.2018.2879812

[38] A. Cotticelli, M. T. Verde, A. Liccardo, G. de Alteriis, F. Lamonaca, R. Matera, G. Neglia, T. Peric, (+ 2 more authors),On the use of 3D camera to accurately measure volume and weight of dairy cow feed, Acta IMEKO 12 (2023) 4.
DOI: 10.21014/actaimeko.v12i4.1633

[39] M. Shanmugam, K. Venusamy, S. Subin, S. Srivatsan, O. N. Kumar, A Comprehensive Review of Haptic Gloves: Advances, Challenges, and Future Directions, in: Proc. of the 2023 2nd International Conference on Electronics and Renewable Systems, ICEARS, Tuticorin, India, 2023, pp. 227-233.
DOI: 10.1109/ICEARS56392.2023.10085607

[40] I. U. Haq, A. Mohiz, G. Spadafora, A. M. Palermo, E. Bilotta, F. Felicetti, F. Lamonaca, AI in the Network of Extended Reality-Enabled Laboratories for STEM Education: Current Applications and Future Potential for Adaptive Learning, Proc. of the I4SDG Workshop 2025 - IFToMM for Sustainable Development Goals. I4SDG 2025, Mechanisms and Machine Science, 180 (2025), pp. 373–382.
DOI: 10.1007/978-3-031-91179-8_39

[41] I. U. Haq, A. Mohiz, G. Spadafora, A. M. Palermo, E. Bilotta, A. Liccardo, F. Lamonaca, The Role of Network of Extended Reality-Enabled Laboratories in Enhancing STEM Education: Bridging Theory and Practice in the Digital Classroom, Proc. of the I4SDG Workshop 2025 - IFToMM for Sustainable Development Goals. I4SDG 2025, Mechanisms and Machine Science 180 (2025), pp. 362–372.
DOI: 10.1007/978-3-031-91179-8_38

[42] M. Habibnezhad, S. Shayesteh, H. Jebelli, J. Puckett, T. Stentz, Comparison of ironworker's fall risk assessment systems using an immersive biofeedback simulator, Autom. Constr. 122 (2021),

103471.
DOI: 10.1016/j.autcon.2020.103471

[43] S. Shakerian, M. Habibnezhad, A. Ojha, G. Lee, Y. Liu, H. Jebelli, S. H. Lee, Assessing occupational risk of heat stress at construction: A worker-centric wearable sensor-based approach, Saf. Sci. 142 (2021), 105395.
DOI: 10.1016/j.ssci.2021.105395