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# Prosthetic Upper-Limb Sensory Enhancement (PULSE): a Dual Haptic Feedback Device in a Prosthetic Socket

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*Abstract*— **This study presents the Prosthetic Upper-Limb Sensory Enhancement (PULSE), a novel dual feedback device completely integrated into a prosthetic socket. The core of the system includes two compact vibrotactile actuators and two silicone chambers in contact with the user's skin. These components provide high-frequency tactile cues for initial contact and surface information (e.g. texture) as well as pressure stimuli related to grasping force. Ten able-bodied participants and one subject with limb loss validated the system, accomplishing an object discrimination task in two different modalities (with and without the feedback). Standardized questionnaires evaluate users' satisfaction and workload, enabling a systematic and robust device assessment. The results show that the PULSE device enhanced performance compared to its absence without causing discomfort for a prosthetic user and able-bodied participants. The findings highlight the potential of dual haptic feedback to enhance sensory perception in prosthetic applications and offer valuable insights for future prosthetic design.**

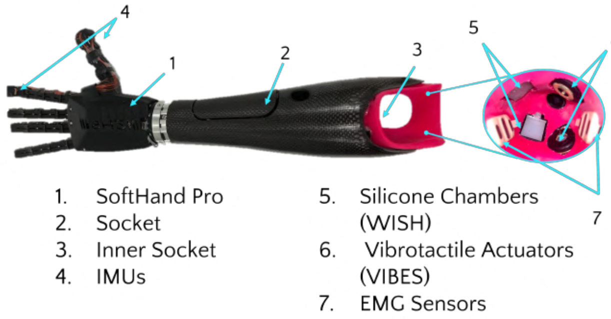

Fig. 1. Overview of the main components of the PULSE ( Prosthetic Upper-Limb Sensory Enhancement) system in a prosthetic socket with the SoftHand Pro robotic hand. A detailed view (right) shows the inner socket and the feedback interfaces.

## I. INTRODUCTION

The human hand's intricate anatomy and specialized neural pathways provide precise motor control and rich sensory feedback from peripheral limb receptors [1], [2]. This feedback is crucial for the central nervous system, offering insights into object attributes beyond vision [1]. However, myoelectric prostheses replace this vital haptic feedback, increasing reliance on visual and auditory cues [3], potentially introducing cognitive challenges and limiting visual information [4].

Several studies dedicated efforts to developing non-invasive haptic devices able to provide tactile and kinesthetic cues, such as pressure, temperature, and vibration [5], [6]. Most of these devices have focused on a single form of haptic feedback, which still limits the overall amount of haptic information the user receives. To address the limitations of these single-modality haptic strategies, recent investigations have illustrated the potential benefits of multi-modality feedback in various haptic interactions and telerobotic applications [7], [8]. In their recent review, Huang et al. [8] explore the potential of integrating multi-modal feedback interfaces (such as those transmitting force, roughness, warmth, and hardness cues) into wearables to enhance the perceptual experience. By combining various feedback modalities, these devices can offer a wider range of tactile cues [9], enabling a more comprehensive understanding of the physical world.

In the study of Markovic et al. [10], the authors presented a vibrotactile feedback bracelet that can convey information about contact, prosthesis status, and grasping force. Six prosthetic users participated in the experiment, rating the feedback positively, highlighting the versatile nature of closed-loop prosthesis control, which can enhance the overall user experience. Abd et al. [11] conducted a study with eleven able-bodied and congenital limb-absent subjects using a dexterous artificial hand paired with a multichannel soft robotic armband. This armband had air chambers linked to BioTac force sensors and vibrotactile actuators to detect object breakage. Results demonstrated successful bimodal haptic feedback for both groups and improved object handling speed with simultaneous control. Despite these benefits, other research found the concurrent stimuli to be confusing, leading to sensory ambiguity [12]. In the study by Jimenez et al. [13], the authors presented a prosthetic hand equipped with a BioTac sensor capable of detecting force, vibration, and temperature. Three separate tactile displays were used to evaluate tactile perception. While these displays effectively provided feedback, the prosthetic user found most tactors distracting for daily use.

Furthermore, a key aspect in this domain is the pursuit of embedded and wearable solutions capable of providing precise stimuli and exhibiting higher stability and adaptability, allowing long-term usability [5]. According to Kim and Colgate [12], an effective haptic system should satisfy the Modality Matching (MM) paradigm by delivering artificial cues that share the same sensory modality as the natural sensation (e.g. pressure as force sensation and vibrotactile stimuli related to surface information [14]), and the Somatotopic Matching (SM) paradigm, by delivering cues in the same place where they would naturally be felt [15], [16]. When these stimuli are applied to the residual limb, they effectively approximate somatotopic sensations [12].

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Based on previous research, our study seeks to assess the effectiveness and user satisfaction of simultaneously transmitting dual haptic feedback for prosthetic devices, without relying on visual cues. Notably, we introduce the Prosthetic Upper-Limb Sensory Enhancement (PULSE), which, to the best of our knowledge, represents the first feedback device fully integrated within a prosthetic socket adhering to somatotopic and modality matching principles (see Fig. 1). The PULSE device builds upon the foundation laid by two haptic feedback systems, the Wearable Integrated Soft Haptic (WISH) device [17] and the Vibro-Inertial Bionic Enhancement System (VIBES) [18], combining their capabilities into a single, unified system. It comprises two silicone chambers (WISH) to convey pressure stimuli associated with the grasping force and two vibrotactile motors (VIBES) to provide high-frequency stimuli capable of conveying surface contact and texture cues.

In this study, we test and investigate the usefulness and performance of the dual feedback with ten able-bodied participants and one subject with limb loss. More specifically, the participants accomplish a modified version of the Haptic Box presented during the Cybathlon 2020 competition[1], discriminating the texture and compliance of multiple objects. Furthermore, we comprehensively evaluate user satisfaction and workload using standardized questionnaires: the System Usability Scale (SUS) [19] and the NASA Raw Task Load Index (NASA-RTLX) workload assessment [20].

## II. SYSTEM DESIGN

The PULSE system integrates both the VIBES and WISH devices. Fig. 1 shows the PULSE device inside the inner socket, connected with an underactuated soft robotic hand, the SoftHand Pro (SHP) [21].

### A. *Dual feedback*

The PULSE system employs two coin-type exciters to transmit surface information, such as texture and first-contact cues. Each exciter consists of a coil that encloses a neodymium magnet. The system also includes two Inertial Measurement Units (IMUs, MPU-9250), which are positioned on the index and thumb phalanges of the SHP. Respect to the previous study [18], the vibrotactile actuator used in this work is the coin exciter (CE) by Dayton Audio (DAEX13CT-4 [2]). This actuator has a high bandwidth of 70-20K Hz, covering the tactile sensitivity range (5-500Hz [22]). It transmits stimuli perpendicular to the skin, a configuration that minimizes the system size compared to tangential transmission. The decision to opt for this actuator was driven by the unavailability of the vibrotactile actuator used in [18], as it had gone out of stock. We conducted a comprehensive evaluation comparing the two actuators, assessing the Just Noticeable Difference (JND) and Absolute Threshold (AT) using established psychophysical methods as outlined in [23] with 15 able-bodied subjects. Our evaluation revealed no statistically significant difference in the two actuators ability to convey texture and contact cues. Consequently, we adopt the CE actuator for this work.

As for force feedback, the PULSE device integrates a pneumatic system. This system consists of two main parts: the feedback interface and the mechanical actuation unit. The feedback interface is comprised of two silicone chambers connected to the mechanical actuation unit via a silicone pipe. The silicone chambers are fabricated with biocompatible silicone (Ecoflex 30[3]), ensuring safe skin contact due to its softness and robustness. The actuation unit is powered by a compact diaphragm pump connected to a solenoid valve and a pressure sensor.

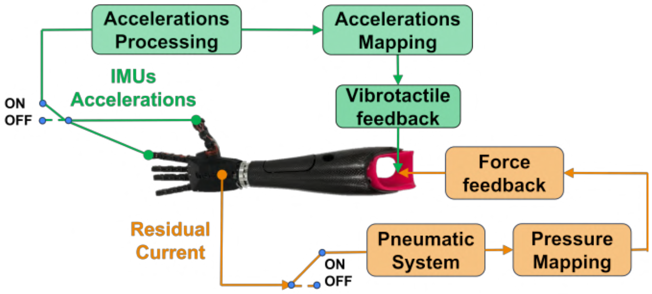

Fig. 2. Control Strategy of the PULSE device: WISH control strategy in orange and VIBES control strategy in green.

### B. *The control strategy*

The SHP is controlled by Electromyographic sensors (EMGs), using the activity recorded from the Flexor Digitorum Superficialis (FDS), and the Extensor Digitorum Communis (EDC) muscles with two Ottobock 13E200 sensors[4].

Fig. 2 shows the control diagram of the SHP with the PULSE system. The control strategy employed to operate the PULSE device combines the control strategies used in the individual devices. Briefly, the pressure stimulation performed by the WISH directly depends on the value of the SoftHand Pro residual current; this information can be used to understand how much force the hand is applying during the grasp of an object. The residual current is computed as the difference between the estimated current and the real current absorbed by the SoftHand Pro motor. Mapping the information from the robotic hand to the feedback device involves associating each hand value with a corresponding pressure value in the device.

The VIBES control strategy involves processing acceleration signals $a = (a_x, a_y, a_z)$ from IMUs. These signals undergo filtering to remove artifacts and free-hand motions, following the method in [24]. Next, using the DFT321 algorithm [25], the three components $a_x, a_y, a_z$ are transformed into a one-dimensional signal $A$ while preserving the same energy as their sum. The DFT321 method, known for emphasizing spectral differences, is regarded as one of the top 321 approaches for offline processing with a focus on perceptual similarity, according to Lee et al. [26]. A scaling factor is then applied to convert acceleration signals into PWM values for vibrotactile actuator activation while considering current limits. This real-time control uses electronic boards [27] for signal recording and actuator control.

Additionally, as shown in Fig. 2 the PULSE is equipped with a switch, enabling the subject to activate or deactivate the two feedback systems at their discretion. This functionality empowers users to activate the specific feedback system (WISH or VIBES) that best suits their immediate needs and preferences, prioritizing long-term usability. As the aim of this study is to ascertain whether simultaneous dual feedback enhances participant experience and whether the sensations are perceived as pleasant, the switch remains

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[1] Cybathlon 2020, [Online], Available: https://cybathlon.ethz.ch/en/events/edition/cybathlon-2020

[2] DAEX13CT-4 Coin Type 13mm Exciter by Daytonaudio, [Online], Available: https://www.daytonaudio.com/product/1172/daex13ct-4-coin-type-13mm-exciter-3w-4-ohm

[3] https://www.smooth-on.com/products/ecoflex-00-30

[4] OttoBock HealthCare GmbH, http://www.ottobock.com/

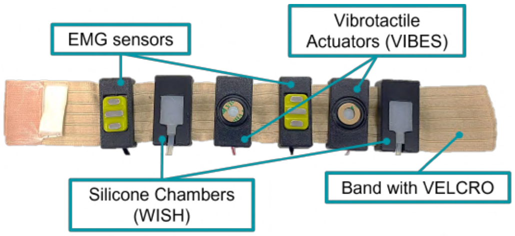

Fig. 3. The bracelet for able-bodied experiments made of adjustable 3D-printed cases for vibrotactile actuators (VIBES), silicon chambers (WISH) and EMG sensors with a VELCRO band with VELCRO for forearm secure fitting.

Fig. 4. Experimental session objects - example of objects without sandpaper covering: wooden and foam cubes, wooden and foam cylinders.

inactive throughout all experimental sessions. Consequently, both feedback systems (the WISH and the VIBES) remain operational.

For an in-depth WISH and VIBES control algorithms analysis, please refer to our prior publications [17], [18].

## III. METHODS

The experimental session assesses participants' ability to recognize various objects with different textures and compliance in the Haptic Discrimination Task. To gain initial insights into the performance of the device before prosthetic user trials, and considering previous studies showing no significant performance differences between prosthetic users and able-bodied subjects (e.g. [11]), both able-bodied participants and a prosthetic user are included in the experiment.

All the experimental procedures are approved by the Committee on Bioethics of the University of Pisa-Review N. 30/2020.

### A. Participants

Ten able-bodied right-handed participants (3 females and 7 males, age mean±SD: 28.4±2.25) and one prosthetic user with left limb agenesis (female, age 43) are enrolled in the experimental campaign. All subjects give their informed consent to participate in the study.

### B. Experimental Setup

The experimental session involves eight objects, which include two foam cylinders, two wooden cylinders, two wooden cubes, and two foam cubes (Fig. 4). These objects are covered with two distinct types of sandpapers: a coarse P80 (with an average grit size of 195$\mu$m) representing the rough object, and a finer P1000 (with an average grit size of 18 $\mu$m) symbolizing the smooth objects. The two sandpapers are chosen with due consideration to their average grit size, prioritizing a significant disparity in surface roughness and following the texture order representation described in [28]. These sandpapers are conformed to the P-grading system established by the Federation of European Producers of Abrasive Products (FEPA). In total, for each shape (cylinder and cube), there are four distinct object categories: rough-soft, rough-hard, smooth-soft, and smooth-hard.

The participant sits comfortably in a chair placed in front of a table. One at a time, the objects are positioned on a table in front of the subject by securely attaching them with VELCRO. A supporting structure made of metallic beams with a black curtain is employed to obscure the object from the participants' view while simultaneously enabling the subject to explore it and facilitating the experimenter in positioning the object (please refer to Fig. 6). A red mark on the table indicates the position of the object under the curtain, helping the subject recognize its placement.

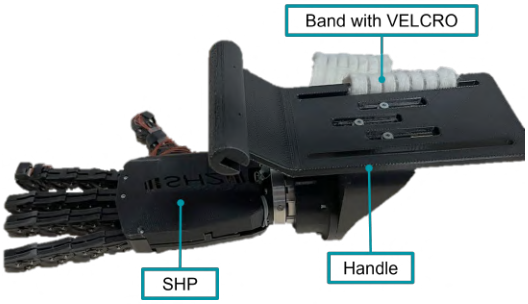

Fig. 5. The handle for the PULSE able-bodied experiments made of a 3D-printed support with a VELCRO band for left-hand secure fitting.

Two separate experimental setups are designed to facilitate the use of the PULSE device and the SHP for both able-bodied participants and the prosthetic user. For able-bodied participants, we have devised a bracelet (Fig. 3) and a handle (Fig. 5). The bracelet includes adjustable 3D-printed cases for two vibrotactile actuators (VIBES), two silicone chambers (WISH), and two EMG sensors. The cases are secured in the correct position, on the forearm of each subject, with a VELCRO band. The handle supports left-hand placement over the SHP to replicate the prosthetic user scenario (left forearm limb agenesis) and features VELCRO bands for secure attachment. A quick disconnect wrist mechanism links the robotic hand to the handle, and the SHP's electronic board is connected to the EMG sensors and the actuators on the bracelet through cables.

For prosthetic users, the PULSE system is also integrated into a prosthetic socket as depicted in Fig. 1. The mechanical structure comprises three key components: the structural frame, which includes the SHP (1), the socket (2), and the inner socket (3) equipped with EMG sensors (7). The mechanical part, housing a battery pack and electronic boards; and the feedback interface, featuring two vibrotactile actuators (6), two IMUs (4) located on the thumb and index phalanges of the SHP, and two silicone chambers (5) integrated into the inner socket.

In prosthetic user and able-bodied subject scenarios, the placement of actuators is guided by spatial constraints arising from the positioning of EMG sensors and the confined space within the prosthesis. Moreover, building upon our previous study [17], which found that actuator positioning had minimal influence on perception, we position the actuators to align with prosthetic user sensitivity and where subjects expect to feel pressure and texture cues on the residual limb. Consequently, we place the vibrotactile actuator linked to the thumb IMU on the glabrous skin, and the vibrotactile actuator associated with the index finger IMU is positioned on the hairy skin. The silicone chambers are situated medially both on the glabrous and hairy skin (please refer to Fig.1).

### C. Experimental Protocol

The Haptic Discrimination Task consists on a familiarization phase and an experimental phase. During the familiarization phase, subjects can freely interact with spherical objects of different textures and compliance for approximately 10 minutes without any sensory isolation. In the experimental

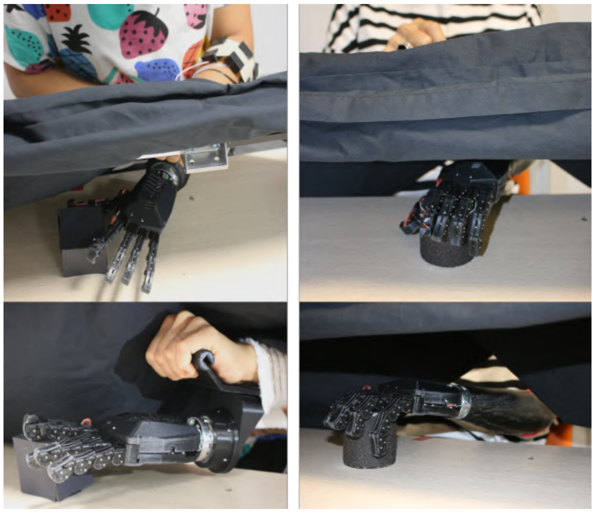

Fig. 6. Haptic Discrimination Task - on the left, an able-bodied participant wears the SHP with the handle and the bracelet while exploring a rigid, smooth cube; on the right, a prosthetic user wears the SHP socket integrated with the PULSE system while exploring a rigid, rough cylinder.

phase, the participant is isolated trough headphones emitting white noise, and each object is concealed behind a curtain. The subject is instructed to use the prosthetic hand to examine the characteristics of each object. The subject distinguishes textures through vibration frequency and intensity on the forearm, and object compliance via pressure — higher pressure indicating greater hardness. In every trial, the experimenter presents the eight objects individually in a random sequence, positioning them on the table in front of the subject behind the curtain. The subject can explore each object without any time constraints. After this, the experimenter reintroduces the same set of eight objects to the participant, maintaining the original sequence, and asks the participants to recognize objects of a specific category (rough-soft, rough-hard, smooth-soft or smooth-hard). The order of these requests is randomized to ensure each category is addressed three times. The subject's responses are recorded for later analysis. Twelve trials (3 for each of the 4 categories) are conducted for two experimental conditions: one with dual feedback (WISH and VIBES always active) and the other without feedback. The initial experimental condition, whether with or without feedback, is randomized for all subjects.

At the end of the experiment, all participants undergo a subjective questionnaire evaluated with a seven-point Likert scale to assess the system and experimental tasks, rating from 1 (totally disagree) to 7 (totally agree). This evaluation procedure is common in assessing assistive robotics and Human-Robot Interaction devices [29]. Moreover, participants are asked to complete the NASA-RTLX questionnaire, which aimed to assess the workload associated with the task through six key questions rated from 0 to 20 [20]:

- ”How mentally demanding was the task?” (mental demand);
- ”How physically demanding was the task?” (physical demand);
- ”How hurried or rushed was the pace of the task?” (temporal demand);
- ”How successful were you in accomplishing what you were asked to do?” (performance);
- ”How hard did you have to work to accomplish your level of performance?” (effort);
- ”How insecure, discouraged, irritated, stressed, and annoyed were you?” (frustration).

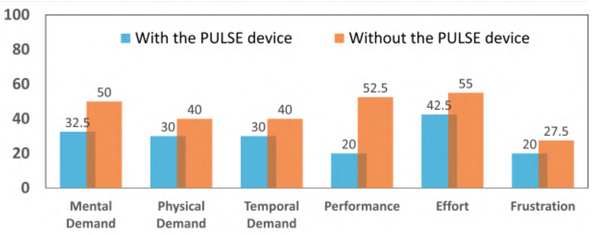

Fig. 7. NASA-RTLX results for able-bodied participants in two experimental conditions: one with the PULSE device (light blue) and one without it (orange). Questions are scored from ”Very Low” (0) to ”Very High” (100), except for the fourth question, where 0 represents perfect performance and 100 indicates failure.

For the performance, 0 means perfect performance, and 20 means failure. For the other questions, 0 represents very low, and 20 signifies very high. Furthermore, a prosthetic user evaluates perceived usability using the System Usability Scale (SUS), a widely recognized standardized questionnaire for this purpose [19].

### *D. Data Analysis*

Confusion matrices and accuracy metrics [30], are used to assess the subjects' performance. We use the Lilliefors test to test subject the non-normal distribution of data. Then, a Wilcoxon signed-rank test is employed to compare the dual-feedback and no-feedback conditions for able-bodied participants. We calculate the NASA-RTLX index for each task by rescaling scores from 0 to 100, taking the mean, and finding the median among participants. Additionally, we use the Lilliefors test to test NASA-RTLX scores non-normal distribution. Thus, we conduct Wilcoxon signed-rank tests to compare the outcomes with and without the dual feedback of the NASA-RTLX scores. Scores for each qualitative questionnaire question, rated on a 7-point Likert scale, are averaged across participants, with median and interquantile range computed for each question.

## IV. RESULTS

### *A. Able-Bodied Participants*

The confusion matrices of the Haptic Discrimination Task are shown in Fig. 8. The mean accuracy with the Pulse device was 85.4%, and without the PULSE device was 60.4%. Since a non normal distribution of the paired data was found we performed a Wilcoxon signed-rank test. A statistical difference was found ($p < 0.05$) between the two conditions. This implies statistically significant differences in subjects' performances when interacting with objects using the PULSE device compared to when they interacted with objects without it. Results of the qualitative questionnaires are shown in the Table I. It's worth highlighting that able-bodied participants were unbothered by the PULSE device and found it beneficial for task execution, as indicated by their responses to questions 2, 6, 7, and 12-17. The NASA-RTLX indicated reduced workload in the dual feedback condition: a score of 35 was found in the dual-feedback condition, in contrast to 43.4 observed in the no-feedback condition. The Wilcoxon signed-rank tests revealed statistically significant differences ($p < 0.05$) between the NASA-RTLX scores with and without dual feedback. Therefore, statistical evidence supports the conclusion that the workload was lower in the dual feedback condition compared to the no-feedback conditions. Fig. 7 shows the median of the

TABLE I: Results of the Qualitative Questionnaires Evaluated On A 7-point Likert Scale (1: Strongly Disagree, 7: Strongly Agree)

| **Questions** | **Able-Bodied** | | **Prosthetic User** |
|---|---|---|---|
| | **Median** | **Interquartile Range** | **Score** |
| 1. It was easy to wear and use the two devices together. | 5.5 | 3.25 | 7 |
| 2. I was feeling uncomfortable using the two devices together. | 2 | 4.25 | 3 |
| 3. I was well-isolated from the external noises during the experiments. | 6 | 0.5 | 7 |
| 4. I was able to hear the sounds made by the actuator/pump of the cutaneous devices. | 2.5 | 2 | 1 |
| 5. I was able to see the cutaneous devices during the experiment. | 1 | 2.5 | 1 |
| 6. The stimuli provided by the cutaneous devices allowed to discriminate different pressure and vibration level simultaneously. | 5 | 1.5 | 1 |
| 7. The stimuli provided by the cutaneous devices enable a correct execution of the task. | 5.5 | 1 | 4 |
| 8. The stimuli provided by the WISH device allowed to discriminate different pressure. | 5 | 2.25 | 1 |
| 9. The stimuli provided by the WISH enable a correct execution of the task. | 5 | 2 | 1 |
| 10. The stimuli provided by the VIBES device allowed to discriminate different texture. | 6 | 1.25 | 1 |
| 11. The stimuli provided by the VIBES enable a correct execution of the task. | 6 | 1.25 | 1 |
| 12. I felt I performed better while receiving pressure stimuli from the WISH device with respect to no feedback. | 4 | 3 | 1 |
| 13. I felt I performed better when I didn't receive feedback from the WISH device. | 2 | 2 | 7 |
| 14. I felt I performed better while receiving vibrational stimuli from the VIBES device with respect to no feedback. | 6 | 1.75 | 2 |
| 15. I felt I performed better when I didn't receive feedback from the VIBES device. | 2 | 1.25 | 6 |
| 16. I felt I performed better while receiving pressure and vibrational stimuli from both the devices with respect to no feedback. | 5 | 2.5 | 1 |
| 17. I felt I performed better when I received no feedback from both devices. | 2 | 1.5 | 7 |
| 18. It has been easy to discriminate the stiffness of an object without any feedback. | 4.5 | 4 | 7 |
| 19. It has been very difficult to discriminate the stiffness of an object without the pressure stimuli. | 3 | 3.25 | 1 |
| 20. It has been easy to discriminate the roughness of the object without feedback. | 3 | 2.75 | 7 |
| 21. It has been very difficult to discriminate the roughness of the object without the vibrational stimuli. | 2.5 | 3.25 | 1 |
| 22. It has been easy to discriminate the stiffness and roughness of the object without any feedback. | 4 | 2.5 | 7 |
| 23. It has been very difficult to discriminate the stiffness and roughness of the object without the vibrational and pressure stimuli. | 2.5 | 2.25 | 1 |
| 24. The stimuli provided by the VIBES did not enable a correct execution of the task. | 1 | 0 | 5 |
| 25. The stimuli provided by the WISH did not enable a correct execution of the task. | 1.5 | 1 | 6 |
| 26. I did not feel bothered by the VIBES stimuli. | 6.5 | 2 | 5 |
| 27. I felt hampered by the VIBES stimuli. | 1 | 1 | 3 |
| 28. I did not feel bothered by the WISH stimuli. | 6 | 1 | 5 |
| 29. I felt hampered by the WISH stimuli. | 1 | 1 | 3 |
| 30. I felt hampered by the WISH and VIBES stimuli simultaneously. | 1 | 1 | 3 |
| 31. I did not feel bothered by the WISH and VIBES stimuli simultaneously. | 7 | 1 | 5 |
| 32. At the end of the experiment, I felt tired. | 4.5 | 3 | 4 |

participant's scores on the questions of the NASA-RTLX test for both experimental conditions.

### B. *Prosthetic User Participant*

With one prosthetic user participant, no statistical analysis was performed. The results of the Haptic Discrimination Task are shown in Fig. 9. The confusion matrices show a major improvement in object category discrimination when the subject wears the feedback device. The mean accuracy with the PULSE was 83.3%, and without the PULSE was 62.5%. Results of the qualitative questionnaires are shown in the last column of Table I. The SUS questionnaire resulted in a 55 score (average SUS score of 68 at the $50^{th}$ percentile). The NASA-RTLX revealed a workload index of 42 in the dual-feedback condition, as opposed to a lower workload of 19 in the no-feedback condition.

## V. DISCUSSION

The Haptic Discrimination Task proved that the able-bodied participants significantly improved the recognition of object categories with the PULSE system compared to those without it. The discrimination accuracy was equal to 85.4% with the PULSE device and 60.4% without it. In Fig. 8, the confusion matrices reveal a significant higher recognition performance of the compliance and texture with the PULSE device, as indicated by the predominant diagonal values, compared to without it. It is possible to notice that the results that we obtained in terms of performance are comparable to those obtained with the NASA-RTLX test and the qualitative questionnaire. Indeed, as shown in Fig. 7, the experimental condition utilizing the PULSE device demonstrates significant reduced workload requirements across all six questions. Moreover, the qualitative questionnaire indicates that subjects did not find simultaneous feedback bothersome (questions 24-31 in Table I). Participants also reported feeling they performed better when receiving both feedback than when receiving none (questions 16, 17).

The PULSE system enhanced prosthetic user performance, with an accuracy of 83.3% compared to 62.5% without the PULSE system. This outcome aligns with performance results from able-bodied participants and is consistent with previous studies (e.g. [11]) showing no significant performance differences between limb-absent individuals and able-bodied subjects. However, it's noteworthy that in terms of qualitative questionnaires, the prosthetic user felt that the PULSE system did not improve performance (as indicated in questions 12-17 in Table I). In correlation with the questionnaire responses, a higher workload index was identified in the feedback condition (42 in the dual feedback condition versus 19 without feedback). Consequently, the System Usability Scale (SUS) score was 55, which was lower than the SUS scores of the individual devices: the VIBES system received a SUS score of 77.5 [18] and the WISH system received a SUS score of 70 [17]. Nevertheless, the stimuli provided by both devices did not bother the subject and the subject did not feel hampered by them (question 26-31 in Table I).

The lack of perceived improvement in performance with the PULSE system can be explained by considering the subject's expertise in using a myoelectric prosthesis and their familiarity with wearing it. Another possibile explanation is that a non-intrusive stimulus may enhance concentration on the task without distractions, leading subjects to unconsciously integrate the stimulus information into the discrimination process. Using the PULSE device more frequently may enhance the perception of the device's utility.

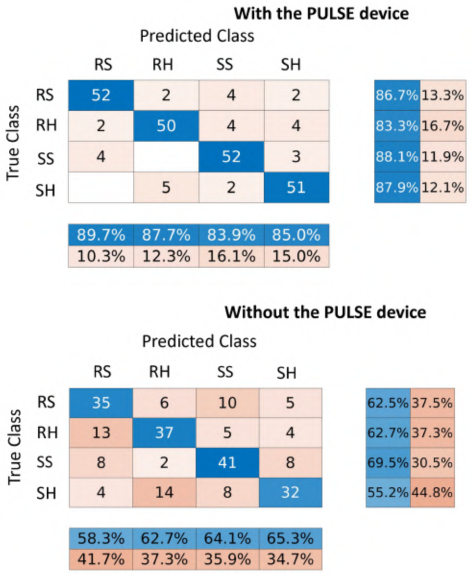

Fig. 8. Haptic Discrimination Task - Confusion matrices with and without the PULSE device for the able-bodied participants. Object categories are rough-soft (RS), rough-hard (RH), smooth-soft (SS), and smooth-hard (SH). The row and column summaries show the relative percentage of accurately (blue shades) and inaccurately (red shades) classified observations for each true or predicted class.

Furthermore, when individually evaluating the two feedback systems, namely WISH and VIBES, both previously received positive assessments [17], [18]. Consequently, the capability to enable or disable single feedback through the PULSE switch holds the potential to enhance the device use and perception of utility.

Remarkably, both able-bodied individuals and prosthetic users achieved accuracy levels that exceeded chance even in the absence of sensory feedback (60.4% for the able-bodied participants and 62.5% for the prosthetic user). This can be attributed to the pivotal role of intrinsic and extrinsic feedback propagation [31]. It's worth noting that, despite the presence of damping elements in the SoftHand Pro, the transmission of vibrations through the socket likely played a substantial role in aiding participants to discriminate between different textures and levels of compliance, which aligns with our earlier research findings with a prosthetic user in [17], [23]. Indeed, our previous research with the VIBES system reported a 40% accuracy rate in texture discrimination without feedback, using deliberately challenging sandpapers with five distinct and hard-to-differentiate types. This study demonstrates comparable results, with a roughly 60% accuracy rate achieved when discriminating solely between rough and smooth textures. Additionally, these outcomes align with our earlier investigations of the WISH system [17], which reported a notably high accuracy in discriminating pressure between two stimuli in a no-feedback condition.

A limitation of our study was the absence of a comparative analysis between the performance of the PULSE device and that of the VIBES and WISH single-modalities in the same task. We recognize the importance of conducting further investigation to delve deeper into the assessments of PULSE device performance. The study focused on evaluating the feasibility and potential user discomfort associated with the simultaneous transmission of dual haptic stimuli. Given the absence of observed discomfort, furture work will compare the PULSE device's performance to that of the VIBES and WISH in the same task to ascertain its effectiveness.

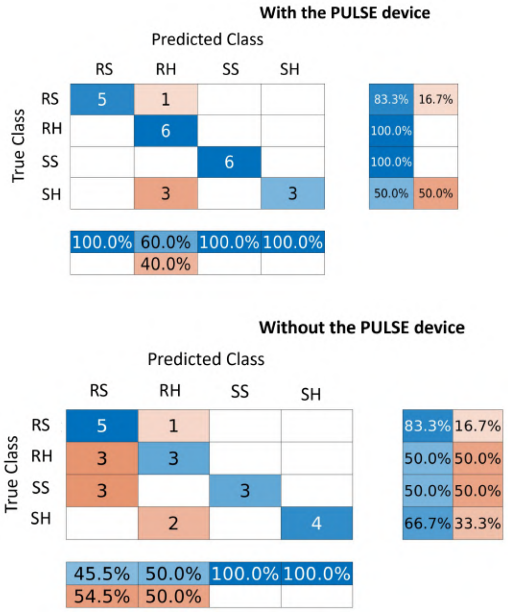

Fig. 9. Haptic Discrimination Task - Confusion matrices with and without the PULSE device for prosthetic user participant. Object categories are rough-soft (RS), rough-hard (RH), smooth-soft (SS), and smooth-hard (SH). The row and column summaries show the percentage of accurately (blue shades) and inaccurately (red shades) classified observations for each true or predicted class.

Moreover, variations in the placement of vibrotactile actuators, silicone chambers, and EMG sensors among able-bodied participants may have affected the outcomes of the study. The qualitative and quantitative findings derived from a single prosthetic user may not comprehensively reflect the overall functionality of the PULSE device. Future tests will evaluate the PULSE device with a larger group of prosthetic users. Furthermore, we will assess the efficacy of the feedback system in facilitating users' transitions between the two distinct feedback types with the switch and evaluate the performance implications of employing more than two coin exciters. However, it is imperative to highlight that the results derived from both prosthetic users and able-bodied individuals exhibit promising outcomes, thereby emphasizing the potential effectiveness of the dual feedback solution.

## VI. CONCLUSION

We presented the PULSE device, a dual feedback system completely integrated into a prosthetic socket. This device can provide information about the grasp force of a prosthetic hand, as well as initial contact cues and texture information. The experimental results with both able-bodied subjects and the prosthetic user demonstrated a high level of accuracy in tasks related to compliance and texture discrimination. These findings are further supported by the qualitative results from the questionnaires, where participants preferred to use the feedback. In conclusion, the PULSE device appears to be a promising solution for delivering dual feedback, offering the added advantage of seamless integration within a socket.

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