On the Somatotopic Mapping of Haptic Feedback from Robotic Supernumerary Limbs

Leonardo Franco[1], Gionata Salvietti[1], Michele Pompilio[1], Simone Rossi[2] and Domenico Prattichizzo[1],

***Abstract*— Supernumerary Robotic Limbs (SRL) represent a new class of wearable robots that can augment human manipulation capabilities. SRL can be controlled through input interfaces worn on the user body and can interact with the environment. Such interaction can be measured and feedback to the human wearer through wearable haptic interfaces. However, human somatotopic arrangement on the central nervous system lacks a location for artificially added limbs. Where is the best location for feedback coming from a robot not directly associated with a part of the wearer's body?**

This paper sheds light on the problem of the best body location for the feedback coming from an SRL as well as on the relation between the position of the input interface and the haptic interface. We have tested four different body locations - shoulder, wrist, hip, and ankle - for vibrotactile feedback coming from the simulated interaction with a robotic extra limb activated using an interface consisting of an accelerometer worn on the user's shoulder. Results from the experiment involving 14 participants demonstrated that the ankle feedback position led to significantly worse performances when having inputs from the shoulder, whereas the other three locations led to comparable results.

I. INTRODUCTION

Wearable robots are usually described as mechatronic systems designed around the human body, with segments and joints matching those of the person it is externally coupled with [1]. This definition perfectly fits all the exoskeletons that have been developed in the last couple of decades. However, in the last few years, a novel generation of wearable robots has been designed not to empower the human joints, but to augment human body functions. These robots have been introduced as Supernumerary Robotic Limbs (SRL) [2] and are designed to be grounded on the human body, but with their own kinematic structures that do not always resemble that of human limbs. Beside the mechatronic challenges in the design of light and portable SRL, there are other two interesting issues to be addressed: how the human can control the SRL motion and how the SRL can feedback to the human important task execution information, *e.g.*, the forces exchanged with the environment. The joint action of interface and feedback is the key toward the usability of this additional limbs [3]. Concerning the input of the interface, several solutions have been proposes ranging from EMG interfaces [4] to measurement of human body motion through, for instance, accelerometers [5].

The haptic feedback is another interesting challenge for SRL. In fact, this wearable robot do not have a direct association with the human body. They are grounded on the body, and so they exchange forces with the human. These forces can be interpreted by the human that can have a proprioceptive information, for instance about the load carried by an extra arm [6]. But there are many other signals, *e.g.* the grasp tightness of a gripper used as end-effector for a SRL that do not have a direct match with the human body. Is it better to display this force where the robot is grounded in the body? Or is it better to display this in another location?

In this paper, we investigated which is the best location for a feedback signal coming from a robotic extra finger controlled by a motion reading interface placed on the shoulder. By lifting up/down the shoulder, it is possible to control flexion/extension of the extra finger. We considered four possible locations for the feedback: the shoulder where the interface is placed, the wrist where the extra finger is body grounded, the hip and the ankle. We measured the reaction time after a vibration burst that was randomly provided in one of the four locations after the activation of the finger motion through the interface. Fourteen participants took part to the experiment. We demonstrated that only the ankle has a statistically significant worsening of the results among the locations.

The rest of the paper is organised as it follows. In Section II, the most relevant literature on wearable robots and wearable interfaces is revised. Section III deals with the experimental setup used and the results obtained. Finally, in Section IV a discussion on experiment relevance and limitation is proposed, whereas in Section V conclusion and future work are outlined.

II. LITERATURE REVIEW

A. Wearable sensing devices

The problem of human body tracking becomes relevant in wearable systems. Several techniques have been developed such as optical trackers, exoskeletons, camera-based systems, and fabric-integrated sensors. Optical tracking systems such as Vicon and Optitrack have high precision and accuracy, but need a structured environment. Exoskeletons allow accurate estimations thanks to their rigid structure and high quality sensors [7], but they are expensive and heavy. Towards the concept of portability, camera-based tracking algorithms have become a widespread solution [8], and commercial devices, like the Leap Motion, have gained success for VR

[1]Leonardo Franco, Gionata Salvietti and Domenico Prattichizzo are with the Department of Information Engineering and Mathematical Sciences, University of Siena, Siena, SI, 53100 Italy leofranco@diism.unisi.it

[2]Simone Rossi was with the Brain Investigation and Neuromodulation Lab, Department of Medicine, Surgery and Neuroscience, University of Siena, Siena, 53100 Italy

applications. However, camera-based solutions have some limitations: RGB-D cameras might not work properly in an outdoor environment due to the infra-red interference, and, in particular for hand tracking, occlusions of the fingers may cause a poor estimation of the hand pose. A viable solution consists in using fabric-integrated devices, *e.g.*, data-gloves based on piezoresistive, fiberoptic, magnetic, Hall-effect [9], or inertial and magnetic sensors [10]. Based on the latter, our group has recently developed a cost-effective sensing glove based on inertial and magnetic sensors to track the human hand without occlusion problems [11], and a headband for controlling a robot arm [12]. EMG recordings can also be used to control a robotic extra limb. The sEMG (Surface Electromyography) provides information on muscle activity that has been inspected in numerous application as motor-control studies, muscular fatigue evaluation, and interface/prosthetics control [13]. In these scenarios, sEMG sensing has been often implemented in wearable devices to monitor patients during daily activities and specific tasks [14], or to provide an unobtrusive control of Human-Machine Interfaces [15]. Many wireless sEMG commercial devices have been developed in the recent years, focusing primarily on data logging for sport and monitoring applications, and on gesture recognition for entertainment or remote control purpose.

Even though we developed and upgraded our frontalis muscle sEMG interface [12], [16], [17], [18] electrode contact stability is still an issue since in prolonged time of use, the user can sweat or undergo muscle fatigue. Moreover, during experimentations we noticed that some user have difficulties in voluntarily moving the frontalis muscle with the sufficient dexterity and in a repeatable fashion. We overcame these problems by developing a new interface for these experiments, a postural back brace equipped with accelerometer and Bluetooth which can remotely give a real-time estimate of the shoulder inclination.

B. Wearable haptics

The majority of haptic devices that are currently available on the market cannot be considered wearable[1]. The pursuit of more wearable haptic technologies led to the development of exoskeletons [19], that, however, are often quite heavy and cumbersome, reducing their applicability and effectiveness. This is why, in recent years, research in the field of haptics focused on the development of a new generation of wearable haptic interfaces [20]. Haptic thimbles [21], [22], haptic rings [23], and haptic armbands [24], have been successfully applied in different applications, ranging from teleoperation and virtual/augmented reality, to human guidance.

Wearable haptic interfaces are designed to provide only cutaneous stimuli usually through vibrations, skin stretch and variation of temperature. This stimuli can be obtained using different type of actuators that can be easily embedded in light and portable devices [20].

[1] `http://www.forcedimension.com/products`, `https://www.3dsystems.com/haptics-devices/3d-systems-phantom-premium`

C. Wearable robots

SRL was introduced in [25] as a novel class of wearable robots that can augment the wearer with one or two extra arms for executing complementary and/or supportive manipulation tasks. The SRL may not only function for endowing the wearer with enhanced precision and strength, but also to extend the range of user's skills, *e.g.* helping the user in maintaining balance as extra legs. In a set of sensitive tasks, *e.g.*, surgical manipulation, teamwork may lead to errors and inefficiency while an extra robotic arm under the user's control can be a solution [26]. Recent studies focused on using SRLs to perform background tasks [27]. SRLs as close co-workers interacting with environment were presented in [28] to guide human hands to attain better stability and accuracy in executing tasks, and in [29], to assist workers in tasks requiring a difficult posture. Unlike the above studies employing SRLs with low DOFs, required for placing the support contacts, to replicate an extra arm similar to human arm, a six-DOF anthropomorphic SRL with hand, named MetaArm, was developed by the Research Center for Advanced Science and Technology (RCAST) of Tokyo [30]. Soft Poly-limb, a highly articulated fluid-driven soft robotic limb capable of complex three-dimensional motion in space, was proposed in [31]. In [32], a wearable arm/forearm was propounded for close-range collaborative manipulation activities, to be mounted on the user's arm to cover an effective workspace despite limited DOFs.

Our research group pioneered the research on supernumerary robotic fingers for grasp support in patients with paretic limbs [4]. Several version of the Robotic Sixth Finger have been designed and tested with chronic stroke patients [2].

III. Experimental setup

The goal of this paper is to study if there is a part of the body where it is preferable to display haptic feedback from a supernumerary robotic finger and if there is a relation with the position of the input interface. Recent studies started investigating how neural body representation is changed when performing task with an augmented hand with an additional robotic finger [33], [34]. However, the role of haptic feedback is still under-explored and one of the first issues to be faced is the body location of this feedback. As a first step toward the study of somatotopic mapping for SRL, we design a simplified experiment involving an interface for extra finger control, the Robotic Sixth Finger [16] and four haptic interfaces located at shoulder, hip, wrist and ankle. In the following we will describe each component in details. The locations were chosen for the following reasons. The shoulder is the place where the input device is located and it is interesting to evaluate if a co-location of input and feedback device may be beneficial. The wrist was the location where the sixth finger was physically grounded on the subject body. The hip and the ankle were chosen for two main reasons: they represent a medium and a long distance from the input device and they have a bony prominence that may be exploited for better transmission of the vibrations.

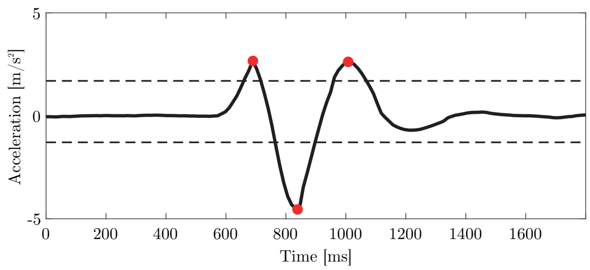

Fig. 1. The solid line represents the signal generated on the x-axis of the accelerometer when the shoulder upward movement is performed. The dashed lines are the thresholds manually selected to find the peaks and the valley, represented by red dots.

The simplified task consisted in moving up the shoulder as if we would like to start finger flexion. After the shoulder gesture is performed, the system generates a vibration feedback, acknowledging the correct shoulder motion, in one of the four locations. As soon as the subject feels the vibration, he/she has to press a button to confirm the feedback perception. The performance metric used in this work is the measure of the voluntary reaction time after the haptic stimulus is sensed by the user. In other words, we evaluated if the perception of the vibration was faster in one of the locations. Moreover, we asked to participants to express their feedback location preference by means of a 7-point Likert scale to collect a qualitative preference.

A. Input device, command extraction algorithm

The human input to the system is obtained by a wearable device that recognizes the shoulder upward movement. We developed this interface by envisioning an augmentative scenario for humans, in which we try to exploit the kinematic redundancy of the human body. The shoulder is an optimal point in this sense, as it can be moved even when both hands are occupied. The device consists of a commercial back brace posture corrector, upon which it was placed an ADXL362 accelerometer, a Teensy 3.2 microcontroller and a RN42 Bluetooth antenna. The microcontroller sampled the three axes of the accelerometer every $13\,\mathrm{ms}$ ($\approx 77\,\mathrm{Hz}$ sampling frequency) and low-pass filtered each channel with a moving average (cut-off frequency $6.8\,\mathrm{Hz}$). Then the filtered data were sent to the computer through the Bluetooth antenna. We calibrated the accelerometer by following the procedure described in [35], which consisted in fitting a 3D ellipsoid to data acquired from the accelerometer which has been rotated with respect to all three axes.

The pre-processed accelerometer signals were buffered and further processed in LabVIEW 2019. The mean of the signal was subtracted to the channels and then was applied an algorithm to detect the upward shoulder movement.

The algorithm is based on the assumption that every subject is able to generate the same wavelet-like waveform. This wavelet signal can be recognized by finding the peak-valley-peak pattern that characterizes it, shown in Fig. 1.

The algorithm takes a moving window of 150 samples ($\approx 2\,\mathrm{s}$) and checks if there is this peak-valley-peak pattern in the axes of the accelerometer. The event recognition is performed by calibrating the system as described in Appendix.

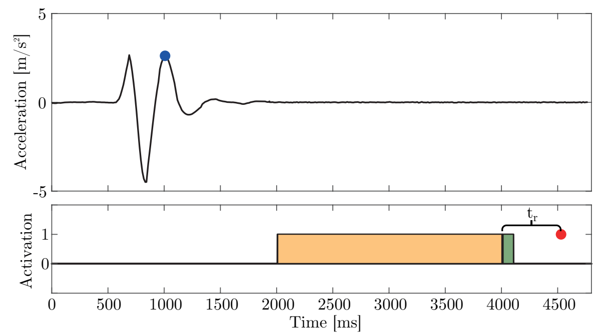

Fig. 2. Timings of the experiment. The upper plot represents the accelerometric signal (solid line) and the movement detection time instant (blue dot). The lower plot represents timings of the system: the orange part represents the time interval in which the feedback could be randomly given, the green part is the vibromotor action and the red dot represents the time in which the button is pressed by the subject. The reaction time t_r is the time that passes from the vibromotor onset time to the button activation time.

B. Feedback system

The haptic feedback was generated by using four Precision Microdrives cylindrical vibromotors. Each of these vibration feedback devices was positioned in a different place of the body: on the shoulder where we placed the input of the system, and in three body places with bony prominences, since the vibration feedback could be clearly sensed, on the styloid process of the ulna (wrist), on the anterior iliac crest (hip), and on the malleolus (ankle).

All the feedback location were selected on the same side of the body where the input system was located (right side of the body) so that the readiness of the patient was not influenced by the button press task, in fact the button is held on the other part of the body as shown in Fig. 3.

C. Task protocol

After the event recognition – a shoulder upward movement – a random delay is introduced to avoid learning effect. The delay can be between 100 and $300\,\mathrm{ms}$ or between 1 and $3\,\mathrm{s}$ or be absent. After the delay, the system actuates one of the vibromotors, giving the acknowledge feedback in one of the four selected body spots. The user are asked to press the button as fast as possible once the haptic feedback is received. An explanatory representation of the timing of the experiment is shown in Fig. 2. We decided to test the subjects responsiveness both with and without this random delay in between the event recognition and the feedback, since it has been found that variability in the fore-period delay influences the reaction time [36].

The haptic stimulus consists in the actuation of a vibromotor for $100\,\mathrm{ms}$. At the same time of the vibration triggering, the microcontroller starts to count time with a millisecond resolution. When the user presses the button, an external interrupt is generated and the microcontroller stops to count. The result in milliseconds is then sent back to LabVIEW where is stored and labelled according to the vibromotor that

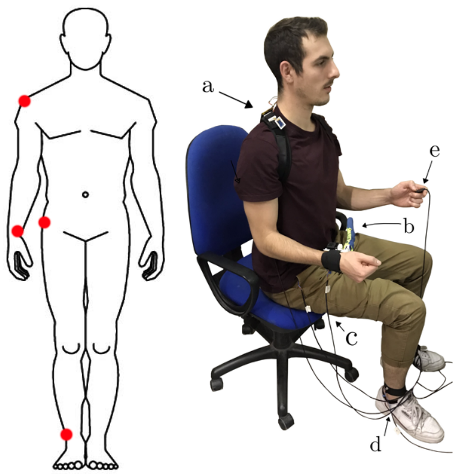

Fig. 3. In the left part of the figure red dots represent the location selected to place the vibromotors. In the right part of the figure is shown the hardware setup mounted on a subject. It is shown by the arrows: the input device and the shoulder vibromotor (a); the output system, the Robotic Sixth Finger, and the wrist vibromotor (b); the vibromotor placed on the hip (c); the vibromotor placed on the ankle (d); the button to measure the reaction of the subject (e).

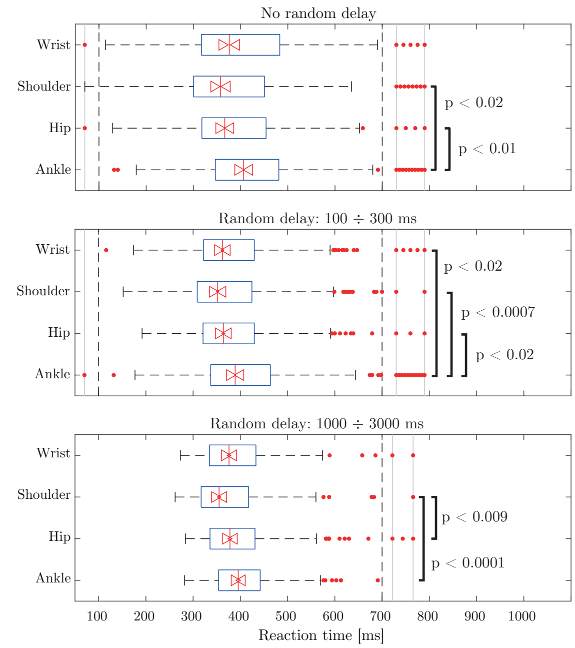

Fig. 4. Results of the experiment under the three delay conditions: without a feedback foreperiod (top), with a variable delay in the range 100 to 300 ms (middle), or with a variable delay in the range 1000 to 3000 ms (bottom).

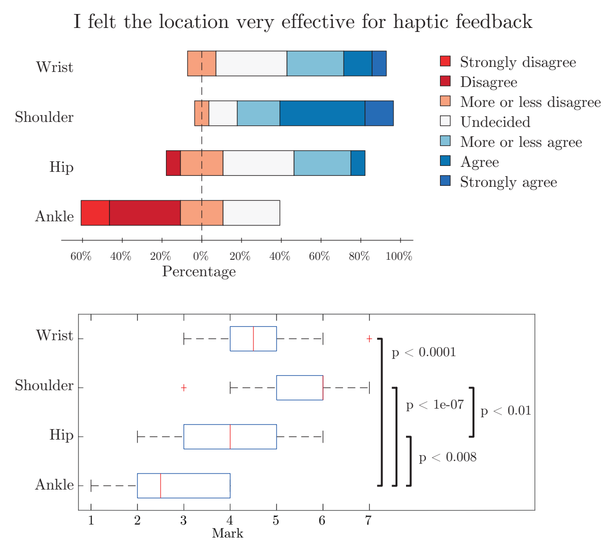

Fig. 5. Results of the 7-point scale Likert questionnaire completed by subjects after the experiment.

was activated after the shoulder upward movement detection. The use of the external interrupt let us take full advantage of the timing precision of the microcontroller, avoiding to rely on a time measured on Windows operative system. During the experiment the subject worn headphones reproducing pink noise to avoid the acoustic feedback of vibromotors. At the end of the experiment we asked to the subject to fill a 7-point Likert scale questionnaire, reporting the sentence "I felt the location very effective for haptic feedback". Each of the four feedback location had on the side the 7 options, ranging from "Strongly disagree" to "Strongly agree".

D. Data collection and results

We collected the reaction time, computed as the time which passes in between the events of motor vibration onset and the voluntary press of the button.

Fourteen subjects aged between 20 and 35 participated voluntarily to the experiment. Each subject contributed to gather 20 reaction time measurements for each vibromotor, for a total of 280 reaction times per feedback location. The experiment was repeated with three delay conditions obtaining $14 \cdot 20 \cdot 4 \cdot 3 = 3360$ reaction time measurements.

The reaction times data distributions passed the Shapiro-Wilk normality test. We ran a one-way ANOVA for each delay condition. The one-way ANOVA did reveal statistically significant differences between feedback conditions as shown in Fig. 4.

It is worth noting that for all conditions the shoulder positioning performed better than the ankle positioning ($p < 0.02,\ p < 0.0007,\ p < 0.0001$). Another important result is that the ankle positioning statistically worsened the performance with respect to other conditions.

Also the 7-point Likert scale questionnaire confirmed the result that the ankle positioning is the worst performing, as shown in Fig. 5.

IV. DISCUSSION

The aim of this work is to make a first step toward the understanding of the best positioning of haptic feedback coming from a robotic supernumerary limb that misses a direct and clear somatotopic mapping. Our investigation started from the hypothesis that when a muscle is activated to start the motion of the supernumerary limb, in our case the shoulder motion that trigger the flexion/extension of the sixth finger, the reaction time to a haptic stimulus is shorter in the body location close to the activated muscle. This hypothesis is sustained by the physiology of the muscles since when a muscle is active, it signals constantly its proprioceptive kinaesthetic feedback both to the cerebellum for movement correction and to the primary somatosensory cortex by means of very fast conduction fibres. Also cutaneous feedback is provided by skin stretch arising from muscle activation [37]. In our experiment, this hypothesis was not confirmed and, apart the ankle, no statistically significant advantaged have been measured in the considered area. One possible explanation to this result is related to the type of feedback. It is possible that a vibration burst interpretable as a discrete event is not enough to elicit the aforementioned neurological signalling that can be considered as a controller for movement correction. A second possible explanation is related to skin physiology. In fact, taking into account that tactile innervation densities are more or less equal in the places where feedback was provided [38], it is possible that the user performs the same in each part of the body, unless the feedback is located very distant in the body, such as the ankle with respect to the shoulder input.

To probe the possibility that the reaction time to the acknowledgement feedback is shorter when the feedback is located in the same body part of the input a different experiment must be adopted. The timing of the subject pressing a button greatly increases the variability of the measurements and more importantly, they are not comparable to bio-potential signals velocity. One possible experiment would be to perform the measurement of the reaction time in a much more invasive way, by using microneedle electrodes to probe muscular onset of muscles responsible for button press [39]. Another, more viable solution would be to evaluate the performances with a different strategy, by leveraging the continuous haptic feedback. This alternative would be non-invasive and of easy implementation, since there are multiple scenarios in which a robot can sense continuous time-varying variables from the environment (*e.g.* feedback proportional to the sensed force of a robot). The subjects that gave an opinion to the experimental setup, claimed that wherever they received the haptic stimulus was not a determining factor. Since the subjects were focused to perform the reaction task of pressing the button, they expected to receive a vibration cue, and, even if the haptic cue was given after a random amount of time, they were somehow ready to react to it.

V. CONCLUSIONS

We concluded that in developing a human-robot interface whose input is placed on the shoulder, physically positioning a haptic feedback channel on the ankle is not a suitable solution. The ankle positioning is inconvenient for a manufacturer since these body parts are far from each other. From an applicative point of view, the ankle is not a practical solution since the user must wear two devices to complete this bidirectional connection with the robot. Data gathered for this experiment did not prove that any of the four locations where we placed the haptic feedback is better performing by examining reaction times to an acknowledgement. However, our results do not exclude the possibility that the haptic feedback could be more useful if placed in one body part rather than another one. The hypothesis we formulated, which would locate the haptic feedback close to the input, was not rejected. Our intent for the future is to further explore this hypothesis by providing a continuous haptic feedback to the subject, *i.e.* a haptic stimulus proportional to some sensed task parameter. Such an implementation is non-invasive and maintains the applicative aspect of the research question.

APPENDIX

To calibrate the system to recognize the input signals of each subject we took the time deltas which occur in the peak-valley-peak signal that characterizes our task for the x and y channels of the accelerometer, and computed a two-dimensional gaussian distributed confidence ellipse with the first 30 movements of the user.

Let the vector Δ be:

$$\begin{aligned} \boldsymbol{\Delta} &= [\boldsymbol{\delta}_{PV} \quad \boldsymbol{\delta}_{VP}] \quad \text{where} \\ \boldsymbol{\delta}_{PV} &= \delta_{PV_1}, \delta_{PV_2}, \cdots, \delta_{PV_n} \\ \boldsymbol{\delta}_{VP} &= \delta_{VP_1}, \delta_{VP_2}, \cdots, \delta_{VP_n} \end{aligned} \tag{1}$$

where $\boldsymbol{\delta}_{PV}$ and $\boldsymbol{\delta}_{VP}$ are the vectors of time deltas which occur between the first peak and the first valley and between the first valley and the second peak respectively. Given that these vectors are Gaussian distributed the ellipse will follow a χ^2 distribution, and for the Wilks' theorem we can scale the ellipse by using the factor:

$$s = -2\log(1-p) \tag{2}$$

where p is the probability value of cointaining all sample points and ranges 0 to 1, and we chose a value of 0.95, meaning that the ellipse will contain 95% of the data points. Given those assumptions we computed the radii $r_{1,2}$ of the confidence ellipse as the eigenvalues of the scaled covariance matrix:

$$r_{1,2} = \sqrt{\lambda[s \cdot \mathrm{Cov}(\boldsymbol{\Delta})]} \tag{3}$$

where the operator λ stands for the eigenvalues and Cov means the covariance matrix. The coordinates for the ellipse center was computed as the mean values:

$$\overline{\boldsymbol{\Delta}} = \left[\frac{1}{n}\sum_{i=1}^{n} \delta_{PV_i} \quad \frac{1}{n}\sum_{i=1}^{n} \delta_{VP_i} \right] \tag{4}$$

The rotation of the confidence ellipse was computed as:

$$\theta = \mathrm{atan2}(\vec{v}[s \cdot \mathrm{Cov}(\boldsymbol{\Delta})]) \tag{5}$$

where $\vec{v}$ represents the eigenvector elements. Once we obtained the confidence ellipse parameters, the system was able to identify the shoulder upper movement of users, by checking if the new couple of values δ_{PV_i} and δ_{VP_i} form a point that lies inside the confidence ellipse obtained in the calibration phase.

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