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Forearm Orientation Guidance with a Vibrotactile Feedback Bracelet: on the Directionality of Tactile Motor Communication

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***Abstract*— User-teacher interaction during the learning and the execution of motor tasks requires the employment of various sensory channels, of which the tactile is one of the most natural and effective.**

In this paper we present a wearable robotic teacher for predefined motor tasks, consisting of a localization system and a wearable stimulation unit. This unit embeds four vibrotactile stimulators which are activated in order to provide the user with a feedback about the movement direction of the forearm in the cartesian space. Stimulators were chosen in order to maximize tactile sensitivity and spatial resolution.

Tactile interface performances in guiding 2 DOF forearm movements were comparatively evaluated with two different sensory modalities: visual and visuotactile, by using a Virtual Reality (VR) rendering of the motor task.

The comparison among sensory modalities was based on two movement indexes ad hoc defined: positioning accuracy and directionality of motor communication. The experimental tests have shown that the system described hereafter is a valuable tool for human motor motion guidance, allowing a successful and useful weighting of concurrent sensory inputs without providing relevant sensory interferences. Compared to visually-guided trajectories, positioning accuracy was improved in visuotactile-guided trajectories. The comparative analysis of the directionality index in all sensory modalities suggests that increasing the number of stimulators could improve the directionality of tactile motor communication.

INTRODUCTION

Teaching the correct way to accomplish a motor task is important in many fields, like rehabilitation, sports or surgical training. In all these contexts it is required that a teacher describes the correct movement, shows how to do it and gives feedback about how the user is performing.

Feedback is crucial to performance both in motor skills learning and execution [1] [2]. It has been shown that the performance can be improved by providing a more specific feedback with a shorter time delay [3]. This feedback requires the user to activate various sensory channels to perceive teacher's inputs.

Through the auditory channel the subject can receive global, coded, high level information about the movement to accomplish; this feedback is abstract and a mental model needs to be created in order to properly parse the information.

Through the visual channel subjects receive from the teacher high level, global information about how the task is accomplished by the teacher or may have feedback about the current position of each visible body segment.

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Tactual channel provides kinestethic information on the position of each joint and tactile information about local touch on skin surface [4]. In such feedback modality subjects need not to map teacher's performance onto themselves, as it is the case with visual feedback, and neither any need to interpret and apply aural information, as for auditory feedback [5]. Motor information through the tactile channel is the most difficult for a teacher to give, as it requires the physical presence of the teacher, which is not always feasible. Such presence can also reduce the size and/or the dexterity of the workspace, besides limiting the possible execution speed.

Tactile stimulation in motor task guidance allows to send to the user information coded by the direction where to move to accomplish correctly a given motor task. This minimally disturbs user's motor performance, without including force interaction, and shows enormous advantages in terms of wearability and cost-effectiveness.

It is also generally recognised that VR environments improve motor learning [6]. The scientific rationale of such environments is based on the key concepts of repetition chances, augmented feedback and improved motivation.

Tactile interfaces have been first employed in the context of sensory substitution for communication and navigation purposes for deaf and/or blind subjects [7]-[11]. They were also employed in the aeronautical field, to optimize information distribution through pilots sensory channels in multi-task environments with high mental workload [12] [13].

More recently tactile interfaces have been tested for human motor performance guidance. Yang et al. [15] presented in 2002 a system which combines visual and tactile feedback for limb motion guidance, where tactile stimulation is provided by a matrix of tactors applied on the thorax.

Lieberman [16] recently focused on tactile interfaces for motion control. In his work a 5 DOF robotic suit was used to guide movements of the upper limb. Vibrotactile motor task guidance was applied in the joints space, recording trajectories with an optical system.

This work focuses on the design of a wearable robotic teacher for forearm movements guidance, based on vibrotactile stimulation. The system employs a magnetic localization system, which avoids the issues of obscured lines-of-sight of optical trackers. Tactile communication guidance is applied in the cartesian space, which we show to be an intuitive feedback modality suited for motor tasks in which the main goal is regulating the position of the end effector (i.e. the hand). The guidance properties of the feedback system were evaluated by applying ad hoc defined performance indexes on the motor task of forearm orientation.

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I. DESIGN PRINCIPLES

The goal of our work is to provide a tactile stimulation which can be clearly perceived by the user in terms of sensitivity and directional resolution. This goal can be reached by generating a proper vibration onto the surface of the skin. For these reasons mechanical studies about skin deformability frequency response have been crossed with physiological data about threshold of vibration perception in frequency and spatial resolution of mechanoreceptors.

Vibrotactile stimulation must be seen as the result of three serial processes. A stimulation unit provides mechanical output in terms of a force applied to the surface of the skin. Skin's deformation can be modeled by kinematic quantities, which modulate mechanoreceptors' response.

A. *Mechanoreceptors' frequency response*

Psychophysical studies on perceived vibration threshold show that 250 Hz is the vibration frequency which can be most easily felt by the user, with a threshold as low as 1 μm in the palm of the hand [17]. But as spatial resolution is also a constraint, we have to evaluate another parameter of mechanoreceptors, which is the size of the receptive field. Pacinian corpuscles have a receptive field much wider than Meissners' (up to 1000 mm^2 against 10 mm^2); this implies that a tactile stimulation at frequencies under 100 Hz improves spatial resolution of vibrations perception [18].

B. *Skin mechanical model*

Many eperimental studies over the last 30 years provided data on skin frequency response [19]-[20]. We modeled the skin as a spring-mass-damper system, with a mass m in series to a viscoelastic load of elastic constant k and damping constant c. The experimental data provided in [20] about skin deformability frequency response were fitted against the predicted model. Linear regression showed a very good regression coefficient ($R^2 = 0.98$), providing the following values of the lumped parameters: c=1.93 Nsm^{-1}, k=744.12 Nm^{-1}, m=8$\cdot$10^{-3} kg, for a contact surface of 40 mm^2.

These results are related to a system whose frequency response in terms of compliance (indentation per force unit) is shown in Fig. 1. This plot clearly shows that a vibrational stimulus above 100 Hz becomes inefficient.

C. *Stimulator properties*

We used miniature DC motors with eccentric masses on their shaft to apply vibratory stimulation. This kind of stimulation depends on the amplitude and frequency of the centrifugal force applied on the shaft by the rotation of the unbalanced mass $F_c = m\omega^2 R$. An electromechanical model has been created to simulate the evolution of the system after a voltage input, using skin impedance values obtained in the previous section. The results are expressed in terms of peak-to-peak vibration vs. shaft rotation frequency and shown in Fig. 2.

According to the reported design considerations, we applied to apply vibratory stimulations in the range [40-100] Hz.

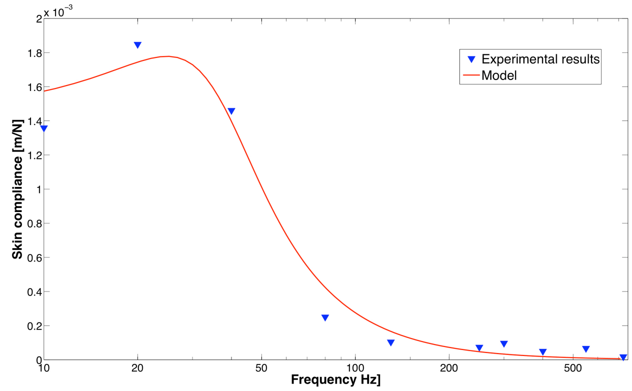

Fig. 1. Experimental vs. model-based data on skin compliance at different frequencies

II. SYSTEM IMPLEMENTATION

The whole system is composed of four functionally distinct subsystems: a magnetic localization system (Polhemus Liberty^{TM}), a stimulation unit (a bracelet with four vibration motors disposed at quadrants), the control hardware and software systems.

A. *Polhemus Liberty^{TM} tracking system*

Polhemus Liberty^{TM} tracking system is made up of one magnetic field source and up to 8 sensors. It has an update rate of 240 Hz with a latency of 3.5 ms, an accuracy of 0.07 cm RMS for position and 0.015° for orientation. One sensor, located close to the wrist in the bracelet (see Fig. 3), has been employed to acquire forearm orientation data through a RS232 connection.

Lieberman employed an optical system and found that it provides to be a very effective but expensive solution, requiring a structured environment [5]. Problems of occlusion during the execution of complex movements could also emerge. The tracking system follows the principle of magnetic field induction and does not suffer from this kind of problem, consisting in a cost-efficient solution, with no optical occlusion.

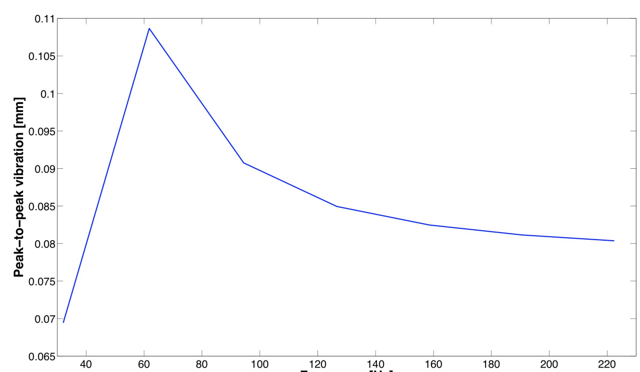

Fig. 2. Peak-to-peak vibration vs. shaft rotation speed for the motor used in system implementation

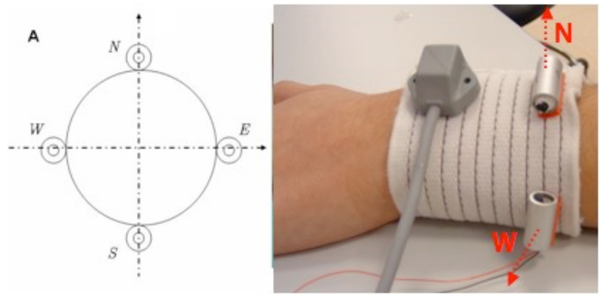

Fig. 3. Bracelet with Polhemus sensor and four motors disposed in quadrants, in scheme from proximal view (A) and in picture (motors are placed on the bracelet for a clearer visualization).

B. Tactile stimulation hardware

The stimulation system is made up of a bracelet embedding four miniature DC motors with eccentric masses (0.5 g) connected to their shafts. They provide a solution suitable for low bandwidth tactile interfaces.

In order to test the guiding performances of the system we chose the 2 DOF task of forearm orientation in space with no concern for its pronation/supination. For this task, the minimum set of motors in agonist-antagonist configuration is four. The bracelet was worn so that motors were applied on the skin with their shaft parallel to it, in such manner that centrifugal force had components in the normal direction to the surface itself, but not in the direction of adjacent motors, in order to minimize localization errors (see Fig 3). Motors were mounted in aluminium cylinders to avoid contact between the skin and the rotating mass. They were disposed in four quadrants and driven at a constant 2.5 V voltage, with a PWM control based on a 1 kHz frequency. For each motor a minimum PWM duty-cycle value in order to start rotation was found to be around 0.2.

C. Tactile stimulation control software

The control software was written in MATLAB^{TM}. It acquires tracking data and provides a proper input for the stimulation unit. Sensor orientation was acquired in the form of quaternions, which describe forearm orientation keeping the sensor in the position shown in Fig. 3.

Tactile stimulation logic was that vibration in one direction (in the cartesian reference frame defined by the motors disposed in four quadrants) suggests movement in that direction, its intensity being proportional to the angular error between current and desired orientation.

Once acquired orientation data through quaternions, rotation matrix R_{01} is constructed through polynomial functions. The first step is to transform forearm's axis director cosines from sensor's reference frame, in which they are expressed by the constant vector $\underline{a}_1$, in the source reference frame obtaining $\underline{p}_{norm}$ vector of unitary norm:

$$\underline{p}_{norm} = R_{01}\underline{a}_1. \tag{1}$$

Then it is necessary to calculate which is the direction where to suggest movement in order to reach the reference position. For the defined task it corresponds to the geodetic path on the surface of the sphere of unitary radius, obtained with the double cross product:

$$\underline{geo}_0 = (\underline{p}_{norm} \times \underline{p}_{ref}) \times \underline{p}_{norm}, \tag{2}$$

where $\underline{p}_{ref}$ is the target position and $\underline{geo}_0$ is the vector containing the director cosines of the geodetic trajectory in the current orientation, expressed in the fixed reference frame. This must be transformed in sensor's reference frame to correctly indicate the direction where to move through the stimulation unit. This is obtained with the transformation:

$$\underline{geo}_1 = R_{01}^T \cdot \underline{geo}_0, \tag{3}$$

which allows to compute the directional cosines of geodetic trajectory in sensor's reference frame.

Tactile feedback was completed by mapping the angular error. Called α the angular error between current and desired forearm orientation (vectors $\underline{p}_{norm}$ and $\underline{p}_{ref}$), the chosen weight function has an exponential form:

$$weight(\alpha) = 1 - \exp\left(-\frac{\alpha}{\alpha_{ref}}\right), \tag{4}$$

where the α_{ref} parameter can be used for tuning tactile stimulation's sensitivity in the proximity of the reference.

The final step was to obtain the correct values of PWM duty-cycle for each motor, which was directly proportional to the component of $\underline{geo}_1$ in that direction, weighted by the corresponding value of the weigth function:

$$DC_i = geo_{1,i} \cdot weight(\alpha) \tag{5}$$

DC_i's sign is thus used to discriminate which one of the two motors located along the same axis must be turned on.

D. Visual presentation through Virtual Reality simulation

To compare guiding results occurring with tactile feedback with those related to visual feedback, a three-dimensional Virtual Reality rendering of the reaching task was provided to the user (see Fig. 4).

The simulation has a fixed point of view which resembles user's point of view of the real task. Forearm orientation must be such that wrist reaches a reference point in the space, drawn as a sphere.

E. Control hardware

Control hardware was implemented with a PIC16F877A microcontroller, devoted to drive a combinatory circuit for DC motors' control according to the duty-cycle values sent via RS232 port. The logical signals are then transformed with a power stage into PWM signals for the motors by means of NMOS transistors. Control logic does not allow two motors on the same axis to be turned on at the same time, as it would communicate a senseless motor information.

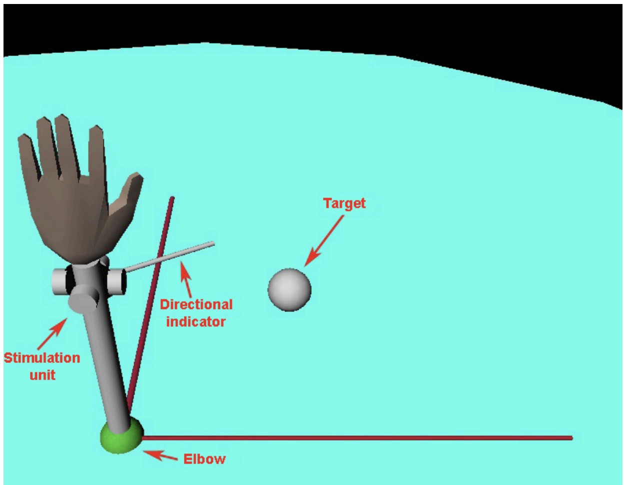

Fig. 4. Screenshot of Virtual Reality simulation, during target reaching. The Directional Indicator points to the geodetic directions towards the target.

III. EXPERIMENTAL SET UP

Five healthy subjects have been recruited to test the guidance system. They were all asked to accomplish the described motor task, guided by three different feedback modalities:

- *visual feedback*, where guidance was provided only with visual presentation of the task as shown in Fig. 4;
- *tactile feedback*, where guidance was provided only with the tactile stimulation;
- *visuotactile feedback*, where both feedback modalities co-existed.

The subjects underwent to a preliminary phase of training in order to get accustomed to the task and to the technology. We did not perform blind and unguided experiments in order to quantify the specific contribuition of proprioception in the performance. For each task the subject was asked to start from the vertical position (Elevation 90° according to angles shown in Fig. 5) and to reach a reference point, selected randomly among the points defined in table I.

25 tasks for each feedback modality have been executed for each reference point (five for each user), with a total of 450 reaching tasks. Each reaching task was recorded and guided for a fixed time length of 10 s, chosing a α_{ref} value of $\pi/30$ rad (6°), which limits the no-feedback angular error range to $\pm$0.025 rad (1.4°).

TABLE I
REFERENCE POINTS DEFINITION

Reference point	Azimuth [°]	Elevation [°]
1	30	30
2	30	45
3	30	60
4	60	30
5	60	45
6	60	60

IV. RESULTS

Two movement parameters are extracted and discussed, in order to obtain a flavour about the performances of the system in guiding a simple motor task.

A. Positioning accuracy

The positioning accuracy taking into account the values of Angular Error Modulus (AEM) function, corresponding to the absolute value of α. The mean value of AEM in a window with temporal amplitude of 1 s is calculated at each sample, when it becomes lower than a threshold value (set to 3°), the target is considered reached. This enables to split the motor task into two phases: the first where the user is trying to reach the suggested forearm orientation, and the second in which the subject tries to keep the position she/he thinks to correspond to the reference.

The first phase of the trajectory has been described by analyzing the reaching time and the regularity of the approaching path (number of zers of the AEM function). These parameters underlined how the visual feedback gives a high-level global information about the position of the target, which shortens the reaching times occurring through the visual modalities in a significant way. The regularity of the approaching path was insted slightly enhanced by tactile feedback, perhaps for the ability of tactile communication to trasmit only information related to the distance and the direction of the target.

Positioning accuracy is defined as the mean value of AEM in the second part of the trajectory, after the target has been reached. Results corresponding to this index are reported in Fig. 6.

We can notice how positioning accuracy is significantly improved by the addition of tactile stimulation to visual feedback. Visuotactile feedback modality is more accurate than visual modality in a statistically significant manner ($p<0.1$), for 4 reference points out of 6. For reference points no. 4 and 6, in which there is not statistical discrepancy, intersection range is very small (point 4, visual modality 0.029$\pm$0.004

Fig. 5. Reference frame used for forearm orientation task (θ azimuth, ϕ elevation.

rad, visuotactile modality 0.021±0.004 rad; point 6, visual modality 0.033±0.005 rad, visuotactile 0.023±0.005 rad). Tactile feedback modality alone does not show any significant discrepancy with respect to the other two modalities. This is a remarkable result and shows how the introduction of tactile communication provides a significant improvement in the accuracy of a positioning task.

B. Motor communication directionality

This parameter was specifically devised to assess how well a given number of motors can guide the task and eventually determine the optimal number. In our case, a set of 4 motor was used in a N, S, E, W configuration as shown in Fig. 7A, where the vibration of motor N elicits a movement in the direction N. In order to elicit movements in intermediate directions, e.g. the NE direction, two adjacent motors (N and E) could be turned on at the same time, with a voltage proportional to the components of the vector $best\_dir$ along its axis. It is not clear, from a cognitive perspective, if the superposition principle can be applied in this case.

The idea behind the Motor Communication Directionality Index (MCDI) is to statistically characterize the error between the desired direction (e.g. the NE direction elicited by the two motors N and E) and the actual direction of motion. The MCDI is defined as the angular error between the desired and current trajectories, computed at the sample in which the first "relevant" movement towards the target happens (at time t_{REL}). For each point of the acquired trajectory, the system suggests to move in a direction ($best\_dir$), in order to reach the desired forearm orientation. It is interesting to evaluate the angle ($theta\_err$) between the previously defined vector and the vector represting the direction where the subject is actually moving ($curr\_dir$), and evaluate the relation between this parameter and the misalignment between the desired direction and the axis of the closest motor ($theta\_dis$). All the defined variables are shown in Fig. 7A, projected in the horizontal plane.

The vector $best\_dir$ was defined as the difference between the first point of the actual trajectory and the target point. A threshold algorithm on acceleration (for the first 2 seconds of the motor task) has been used to correctly identify the instant t_{REL} in which the first relevant movement towards the target occurs. At t_{REL} the vector $curr\_dir$ is computed, as the derivative of the projection of the trajectory in the orizontal plane, obtained by averaging subsequent samples, in order to filter human tremor.

At t_{REL}, the orientation of the reference frame defined by the stimulators was evaluated, in order to obtain without any ambiguity the angles θ_{dis} and θ_{err}. A graphical representation of the defined variables for one of the acquired trajectories is shown in Fig 7B.

The modulus of θ_{err} ($|\theta_{err}|$) has been computed and plotted versus the remainder of the division of θ_{dis} by $\pi/2$ ($\theta_{dis,n} = \theta_{dis} \bmod \pi/2$, this operation groups occurrences in which each stimulator axis is aligned with the $best\_dir$ vector). For every motor task a couple of $\theta_{dis,n}$ and $|\theta_{err}|$ values has been calculated and plotted in the plane $\theta_{dis,n}|\theta_{err}|$. A histogram which averages the values of $|\theta_{err}|$ among six intervals of $\theta_{dis,n}$ (from 0 to $\pi/2$ rad, with amplitude of $\pi/12$ rad) is shown in Fig. 8.

We can notice how the distribution of the mean values in the various intervals shows a tendency which is substantially different for the three feedback modalities. Tactile feedback maximizes the directional error in intervals where maximum misalignment occurs (regions 3 and 4, corresponding to misalignments within $\pi/6$ and $\pi/3$ rad), whilst intervals with minimum misalignment (1 and 6, corresponding to misalignment of less than $\pi/12$ rad) from the nearest vibrating motor provide minimum directional errors. Visual and visuotactile feedback modalities do not show this tendency, providing similar directionality indexes.

During tactile feedback guidance, in intervals 3 and 4

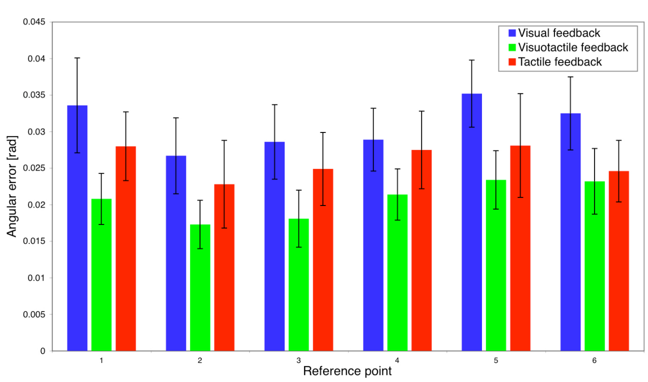

Fig. 6. Residual error after target reaching for each reference point. Every bar represents mean value of 25 tasks (five tasks for every subject), with error bars defining confidence interval (p<0.1).

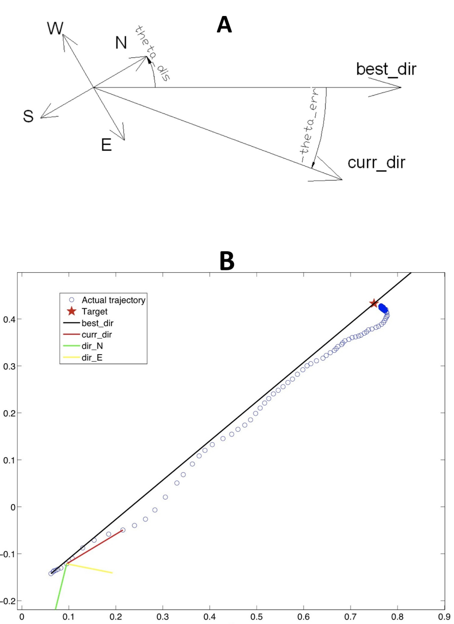

Fig. 7. (A) Definition of useful entities for the evaluation of communication directionality and (B) example of the application of the algorithm on a trajectory for determining the above defined vectors and angles.

the information is transmitted by means of a simultaneous vibration of two adjacent motors, whilst in intervals 1 and 6 the vibration is mainly provided only by one motor, whose axis is almost aligned with the $best\_dir$ vector.

The comparative analysis of the results in the three presented feedback modalities shows that a number of four motors and the subsequent logic of simultaneous vibration of two adjacent stimulators may be inadequate in terms of the directionality of motor communication.

V. CONCLUSIONS AND FUTURE WORK

The wearable robotic interface has shown to be appropriate for guiding simple movements of the upper limb.

Stimulators' vibration frequency was chosen in the range between 40 and 100 Hz. These values emerged taking into account data on human performance in vibration perception and by creating a simple mono-dimensional mechanical model of skin's frequency response.

The interface showed to be able to be effective in communicating through the tactile channel directional information in the cartesian space concerning motor tasks guidance.

The simultaneous use of both sensory modalities did not provide negative interferences, with the subjects being able to make successful filtering and weighting of inputs. In the first part of the trajectory, the subject mainly interprets inputs coming throguh visual feedback modality, which is useful for a global guidance towards the target. In proximity of the target the user privileges the tactile feedback to fine-tune his current forearm orientation, improving positioning accuracy. This successful result may be also due to the discontinuous mapping between vibration and distance from the target provided though tactile feedback, which indicates target reaching. Visual modality can also be endowed of such event cue in Virtual Environments, thereby probably providing similar results in terms of accuracy. This aspect has not been verified as it goes beyond the objectives of our work, which does not aim at verifying psychophysical hypotheses on sensory inputs processing by humans but only at giving a flavour on the design choices for a wearable system apt to guide movements in unstructured environments.

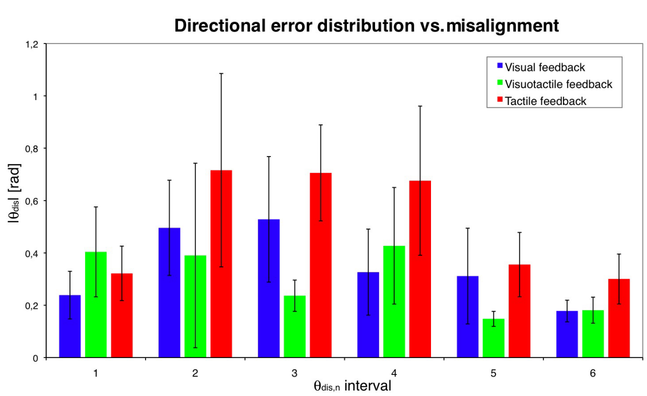

Fig. 8. Histogram of $|\theta_{err}|$ distribution in intervals corresponding to various disalignments. Intervals are 15 degrees wide and cover the range of $\theta_{dis,n}$ values between 0 and 90 degrees.

The system can be scaled up in order to provide an efficient, low cost interface for the guidance of more complex motor tasks. In this perspective, a parameter to be taken into account is energy consumption, as current stimulator system requires up to 80 mW per bracelet.

Future work will concern guiding complex articular movements and not just the reaching of a predefined final position, taking also into account movement velocity for providing input.

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