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TESI DI LAUREA MAGISTRALE

Study of a wearable technology to help indoor climbing for blind people

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To my family

Abstract

This thesis reports the stages of development of a haptic device to help visually impaired people during indoor climbing training sessions, developed in collaboration with Università degli Studi di Siena. In the thesis, after an introduction on some fundamental concepts to keep in mind in indoor climbing, the state of the art related to haptic interfaces and to sport climbing is presented. After that the hardware and software developed will be described. Several tests on haptic perception are also presented; in particular, the procedure of each single test and results obtained. The thesis ends with some considerations on the developed prototype and a discussion on possible future works.

Contents

List of Figures

Chapter 1

Introduction

The thesis is done in collaboration with Università di Siena. During the development of the thesis in Turin, the student moved to Siena to report his doing and test his prototype.

1.1 Indoor climbing: bouldering

Sport climbing is increasingly being practiced in Italy. Indeed,the number of Fasi (Federazione Arrampicata Sportiva italiana, the Italian federation of sport climbing) members jumped from 29362 members in 2017 [1] to more than 43400 in May 2022 [2].

Sport climbing can be divided in two major groups: indoor climbing, practiced inside a facility equipped with a climbing wall, and outdoor climbing (rock climbing), practiced on natural formations. For indoor climbing the artificial climbing wall has handholds with different shapes and colours. The color of the handholds is important, as it is typically used to point the correct route to follow while climbing, handholds with same color are part of the same route.

The disciplines of Indoor Climbing are 3:

1. Bouldering: on a wall from 3 meters up to 8 meters the climber has the objective to perform particular sequences of chained and dynamic movements, usually few (8-10), but extremely difficult in 4 minutes. They can use only a prefixed series of holds.

2. Lead climbing: the athletes wear climbing harness connected to a rope. While ascending the route (in a wall of 15 m) they attaches cabiners to pre-fixed spots. The objective is to climb as high as possible.

3. Speed: the objective is to climb a standard wall as fast as possible.

The main objective of this thesis is to help blind people practice bouldering using haptic feedback on the user.

The main problem for blind people is to identify which hold to use for following the predeterminate route. During Paralympics a guide has the duty to be the eyes of the para-athlete and guide them during their ascension of the route. As it can be seen in 1.1 the process of blind climbing can be summed up to these 6 interactions:

1. an expert trainer (route setter) sets the climbing wall and the different paths to follow(routes).

2. another trainer (that will be the guide of the blind athlete) visually studies the climbing route.

3. the guide instructs verbally the athlete.

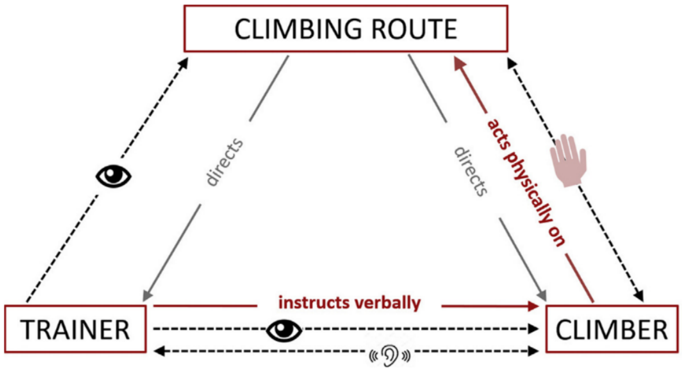


Figure 1.1: Guide-climber interactions [13]

4. the guide uses the sight to have feedback on the position of the athlete.
5. the guide and the climber exchange feedbacks on the route using verbal communication (in this way the sense used is hearing).
6. the climber acts physically on the route (touching the holds and grappling only on the holds of that coloured route).

Figure 1.2: Example of climbing wall from [13]

The role of the trainer is very important: he has to translate visual information in audible information by verbally locating the footholds and the handholds. In particular, these ones are located using an analogy with the hours of a clock [3]. This need of ongoing assistance is a limitation to the athlete. In particular, it limits the autonomy of the athlete and the frequency with the athlete can train: If someday the guide is not available, the athlete is forced to skip the training session. The main objective of this thesis is to develop a prototype able to guide the climber is this particular scenario using haptic sensing.

1.2 Haptic Interfaces

Haptics comes from the greek word *haptesthai*, which it means "to touch". As defined in [5]: "In the psychology and neuroscience literature, haptics is the study of human touch sensing, specifically via kinesthetic (force/position) and cutaneous (tactile) receptors, associated with perception and manipulation. In the robotics and virtual reality literature, haptics is broadly defined as real and simulated touch interactions between robots, humans, and real, remote, or simulated environments, in various combination." In particular, haptic interfaces are robotics device that use the sense of touch to communicate with the user and or let the user feels the sense of touch in a remote or a simulated environment [5].

In this particular exam case (bouldering for visual impaired athletes) the sense of touch and the sense of hearing are the most used senses by a blind person during climbing.

Hearing is the most used sense when climbing and therefore also the most overloaded sense. It is used by the blind both to receive information about the route from a guide but also in case of danger or urgent communication from the guide or other members of the climbing gym. This leads to not recommending the use of headphones to indicate the next grip during blind climbing, because they would risk to totally "occupy" the sense of hearing for emergency communications (such as the presence of a person passing under the wall while the blind athlete climbs and so on).

To not overload the sense of hearing we opted for the use of a haptic interface. The prototype touches the person in different points of the body not in contact with the climbing wall, managing to communicate the next movement on the route, without diminishing the safety and perception of external stimuli of the end user.

A notable case in literature about the use of haptic sensing is the one in [4]: in particular, an algorithm of optimal reciprocal collision avoidance is used. In the article is described how effective is the haptic-guidance of several blindfolded users. They try to follow a predetermined road path using directional cues indicated by a haptic-interface. In this study blindfolded people are guided using two vibrotacticale armbands placed on the forearms. Each interface is composed by an Arduino board, a li-ion battery and two vibrotactical motors attached to an elastic band, depending on which way the motors vibrate the user is able to identify in which direction to move. [4] shows it is possible to guide a blind user with good precision, and only slightly slower than a sighted individual. This is the inspiration to develop a haptic prototype to guide blind people while climbing.

1.3 Briefly explanation of Xsens Awinda

Xsens Awinda technology has been used to track the user during climbing. It is a wearable wireless motion tracker. To use the devices measurements of certain points of the body are taken as indicated in [8]. Then 17 inertial and magnetic motion trackers are placed all over the body according to [7]. Each sensor unit is composed by a 3D accelerometer, 3D gyroscope, and 3D magnetometer.

Data from the wireless units are streamed to MVN analysing software and are processed and united with a 23 link (scaled) bio-mechanical model of the human body [6]. After a first calibration it is possible to stream the data to a third party software (in the case on this thesis is a Matlab program). The data possible to stream are absolute position and orientation of the segment, right handed (Euler, Quaternion), joint angle data, absolute segment position, velocity and acceleration, absolute segment orientation, angular velocity, angular acceleration, motion tracker kinematics (Absolute sensor orientation and free acceleration and Sensor-local acceleration, angular velocity and magnetic field), centre of mass and time code string.

As it will shown in Chapter 3, part of these data is used in a Matlab program to indicate how to reach the next correct hold to climb successfully.

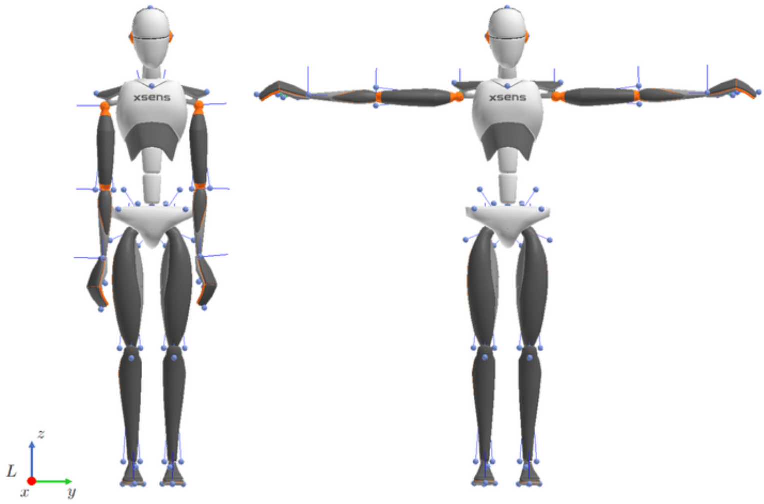


Figure 1.3: Bio-mechanical model of the human body in N-pose (on the left) and T-pose(on the right);this two poses are used for calibration of the Xsens.[6]

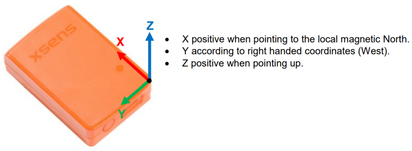


Figure 1.4: xsens awiba single unit [10]

1.4 Useful concept: PWM, BLE

In this section it will be presented a swift introduction on some useful concept used in this thesis.

1.4.1 Pulse Width Modulation (PWM)

A motor after applied a dc power source it doesn't reach immediately the desired velocity but it will need a rise time. The same is if we reduce the power supply, the motor will not instantly reach the desired velocity. Switching the power on and off of the dc power supply we can control the velocity of a motor. So controlling the width of the pulses we are able to control the velocity of a motor, from here the name Pulse Width Modulation(PWM)[26]. One of the main characteristics of this digital signal is that, differs from other digital signal, the time of on and off condition can be varied. From here other than frequency to define a pwm signal we need the duty cycle: the percentage of time when the pulse is in on condition against the total period of the signal. So for example a pwm of 40% it results in a 40% of the period in on condition and 60% of the period in off condition. The micro controller used in this thesis can generate pwm signals. So they are used to control the velocity of the vibrating motors and so to control the haptic output on the user.

1.4.2 Bluetooth low energy(BLE)

Bluetooth low energy (BLE) was introduced in 2010 in version 4.0 of Bluetooth specification. Different from the Bluetooth, it has a lower battery consumption: this is because the BLE communicate using burst message, lower bandwidth data transfer and because BLE tries to turn on sleep mode as much as possible. The range of BLE communication variate on the configuration

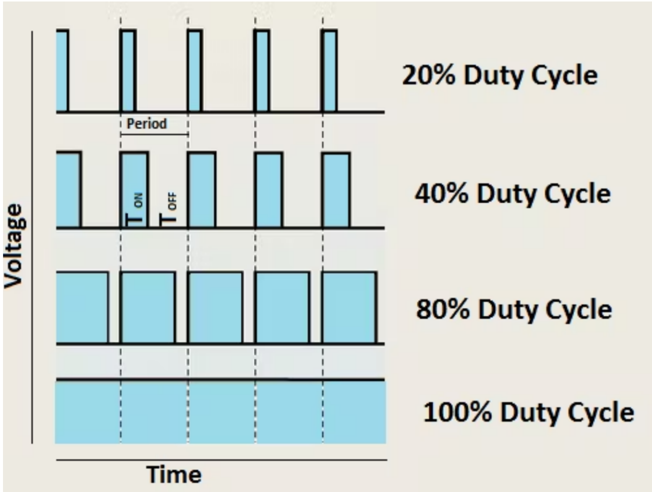


Figure 1.5: Graphic visualization of pwn using different duty cycles from [23]

used, in particular depend on the hardware component of the two radio communicator and on how fast a data is sent. Using lower data rates and lower modulation it is possible to reach longer range (up to 400 m)[24]. But long range means high power consumption due to a message sent slower.

We need at least a peripheral device and a central device to communicate using BLE. A central is the device that initiate the connection request to an advertising peripheral. It is the device which sustain the more computational work and power consumption. Peripherals are the devices that accept the incoming communication. Centrals can be connected to multiple peripherals and vice versa peripherals can be connected to multiple centrals. Same device can be at the same time peripheral for some devices and centrals for other connections. It is important that the role of peripheral and central is decided the moment the connection is established. A central to find a peripheral need to scan for the advertising packet (time for scanning is the scanning window and how often it scan is the scan interval). The advertising packet is a message sent from the peripheral to be individuate. It contains various data depending on the type of packet but usually it has, at least, the name of the peripheral and the service that the peripheral provides. The advertising packet is send in time interval, called advertising time, that range from 20 ms-10.24 s [24] depending of the device. When the central find an advertising packet, it sends to the peripheral a connection request. The peripheral responds with a peripheral respond packet to let form the connection. The attributes of a peripheral are organized in services and characteristics. Similar characteristics are often inside the same service. Characteristics are some data that the BLE device communicates. Each characteristic has some descriptors. The permission descriptors are the ones that permit the communication; they are four [25]:

- None: the characteristic can't be read or written by the central;
- Readable: the characteristic can be read by the central;
- Writable: the characteristic can be written by the central;
- Readable and writable: The attribute can be both read and written by the central.

1.5 Thesis contribution and structure

The objectives of thesis is to:

1. Search and analyse the main problems of blind people during bouldering activity.
2. Determinate how to use haptic sensing to solve related problems.
3. Develop a haptic device able to help them climb up more independently.

In order to achieve these results first a preliminary study of the literature is done. Then a first simpler prototype is developed. After that some tests are executed. Then step by step other features are added on the prototype. Then other test on detection rate of haptic stimuli are done. The thesis structure is the following one: after this brief introduction to blind climbing and model used during prototype, in Chapter 2 it will be a briefly state of the art of climbing guidance technology, on blind people and haptic project that inspired this thesis. In Chapter 4 it will be described the testing and their overall evaluation during this study that lead to the development of the prototype. In Chapter 3 it will be described the prototype and its different configurations (both hardware and software). Chapter 5 is to present some conclusion on the current prototype and its possible improvements in future works.

Chapter 2

Related Works

The objective of this chapter is to present some works related to the developed haptic interface and other sources that inspired the following thesis.

In particular, some works on haptics will be described (in particular those provided by the team of Professor Pratichizzo, who welcomed me in Siena for the thesis), studies about the sensitivity of body parts to different impulses (which helped to decide the positioning of the prototype developed in this thesis), other examples of wearable and not wearable products used during climbing activities and studies on indoor climbing techniques.

2.1 Haptics

In wearable technologies the most used stimuli to the end user are auditory and visual ones. As stated in Chapter 1, they can be overloaded. The two used kinds of haptic interfaces are the kinaesthetic ones and the cutaneous or tactile ones. The former interfaces due to the need of exercising a force on the user tend to be bigger in volume and more energy consuming. The latter could be not explicitly generated by a haptic device, but if tactile receptors are still stimulated, it can be defined as haptic device [5].

For example, a vibrating motor isn't strictly a haptic actuator but if applied on the skin of the user, it can deliver some haptic stimuli changing its frequency or it's amplitude. Some examples of vibrating motors used as haptics actuator can be seen in [19], [14], [15].

Figure 2.1: Example device from [19].

In [19] it is presented a remote guidance system for visual impaired people. Due to partial or total blindness, these subjects may encounter many difficulty during their day life moment, so they can have the needing of a guide. Their solution is to guide them using 2 vibrotactile bracelets, a phone and a cane. The phone, attached on the chest of the end user, streams a video of the surrounding area to a remote volunteer. The volunteer guides the visual impaired person by sending haptic stimuli trough the 2 vibrotactile bracelets in order to reach the desired location (the cane was used as usually, to avoid some immediate obstacles to the blind walker). Similar to this project in the thesis prototype, we will use vibrotactile motors distributed on the body to guide a blind person on a climbing wall, instead of using it on a sidewalk, changing the motion.

In [15] it is presented a haptic guidance policy to steer the user along predefined paths and try to evaluate if it is possible to compensate the delay that human have to perceive and do haptic guidance stimuli. The tests are computed on blindfolded people and on people without vision impairment. As stated in the article "results revealed that an average error of 0.24 m is achieved by using the proposed haptic policy, and that the predictive approach does not bring significant improvements to the path following problem for what concerns the distance error"[15], but in case of blindfolded people, it reduced the variability of the mean value velocity of them. It discourages me from compensating the actuation delays that humans have when perceiving the haptic stimuli in order to improve the guide on the route.

In [14] the authors used a vibrotactile device similar to the one proposed in the first phase of development of this thesis to guide a wrist of the wearer to a desired path in the 3D space. In particular they note that in a range of 80-200 Hz a variation of 30 Hz was perceived. This will be very usefully to determinate in which way we can vibrate our vibrating motors to be best perceived by the climber.

Figure 2.2: Example device proposed in [14]

2.1.1 Sensibility of the different body loci to haptic stimuli

The following two works are used as based to decide the design of this thesis project and where the vibrating motors should be placed.

In [17] they, using two experiment using 5 different vibrations on 13 body loci, checks the detection rate and the response time to these 5 intensity vibration by a vibromotor. In figure 2.3 it can be seen the indicative position where the haptic actuators are distributed:

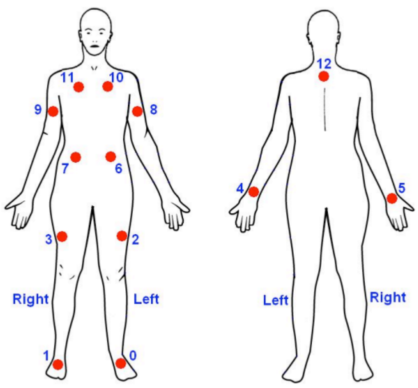


Figure 2.3: Haptic actuator position in [17], for the precise position see the article

From these tests, the body parts, with better detection ratio during walking, are in order:

wrist, spine, arm, foot, thigh. On the contrary, thigh and foot have the higher reaction time. Another notion is that stronger vibration are perceived faster.

During this test the users prefers wrist, arm and spine for directional guidance. Then we can see that moment decrease the detection rate in each part of the body. Expecting a vibration, increase the detection rate.

In climbaware project [18] it is designed a device to test which kind of signal(tactile, hearing or visual) is better perceived, during climbing, in different body parts. The authors, during their tests, send to 12 climber different kinds of stimuli(vibration,sound,light). After conducting the test, they find out that the best notification channel is sound, but directly followed by tactile.

In figure 2.4 they show witch body parts are considered by the testers as more sensible to vibro-tactile input at the end of the test.

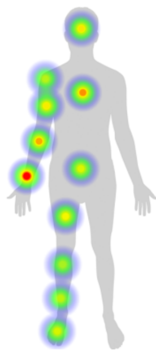


Figure 2.4: How much each body part is sensible to haptic input; the redder the point the better that body part was considerate perceivable[18]

2.2 Other useful works

Climbing as pair in [13] is essential to understand the dynamic of instruction that the guides uses in indoor climbing to help the visually impaired athletes. The main information, that we can extrapolate from all the climbing route studied in this paper, is that we can divide the climbing motion in 2 basics step: first move the foot to the foothold, and then move the hand to reach the handhold.

In [22] it is showed an app able to scan the boulder climbing wall. So to track the climbing wall is used the corresponding app-generated virtual map. They propose the use of the wall as a huge traceable in the augmented reality. Doing so, they state that the occlusion of the camera could be negligible. This work will be useful when we need to scan the climbing wall to create the virtual map in the future part of the development process.

Chapter 3

Prototype

3.1 Introduction

As suggested in [12], when considering technique in sports, we need to focus in the sequence of movement and not on how the task is performed.

As shown in [3], the climb is accomplished with a series of movements that can be articulated in two basic steps:

1. Putting the foot on the foothold
2. Putting the hand in the handhold and grasping it

The decision in the choice of the foothold is important, because it supports the body when the handhold is grasped. It is also reasonable to think whenever it is possible to move both the dominant leg and the other one, the user would prefer to reach first the footholds with the dominant one. The algorithm of the prototype comes from these two thoughts. From signals taken from vibrating motors placed in different parts of the body, 2 main information are sent: which of the 4 limbs to move and in which direction that limb should move to.

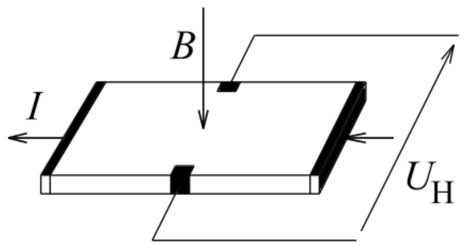


Figure 3.1: Hall sensor working principle: when a magnetic field is perpendicular to the sensor it will generate a voltage difference.In figure B is a magnetic field. I is the current that pass through the hall sensor. Uh is the generated voltage.

In the first part of the thesis it was thought to use magnets and Hall sensors. We should have positioned small neodymium magnet in each holds that needs to be reached. The hall sensor is able to give an output difference of voltage given a perpendicular magnetic field. After connecting the hall sensor to a micro-controller, it was tested if it was able to perceive the magnetic field. But the hall sensor to perceive the small magnet needs to be put too much near with the magnet. This is not acceptable in our application because:

1. During climbing the hand of the user rotates and the orientation of the hall sensor will be such that it will not perceive the change in the magnetic field.

2. We could increase the dimension of neodymium magnet to increase the magnetic field, but this isn't a feasible solution, because the smaller footholds called "chips" could be around 2 cm of diameter (an example in 3.2). Bigger magnet can be swapped for other footholds with catastrophic consequence (not only the magnet is not part of the route, failing the climb, but the magnet is not able to sustain all the force applied to the foothold ending with the fall of the user).

Figure 3.2: Example of "chips" in a bouldering wall, from [11]

3.2 Description of the prototype

From these previous considerations, the following prototype is developed: a map of real holds is created in a virtual environment. Using the Awinda Xsens technology on the subject, we track the user in the virtual environment, then using some vibrating motors (controlled by changing the duty cycle of a pwm signal), some impulses are given to the limbs of the end user to guide him to reach the final objective.

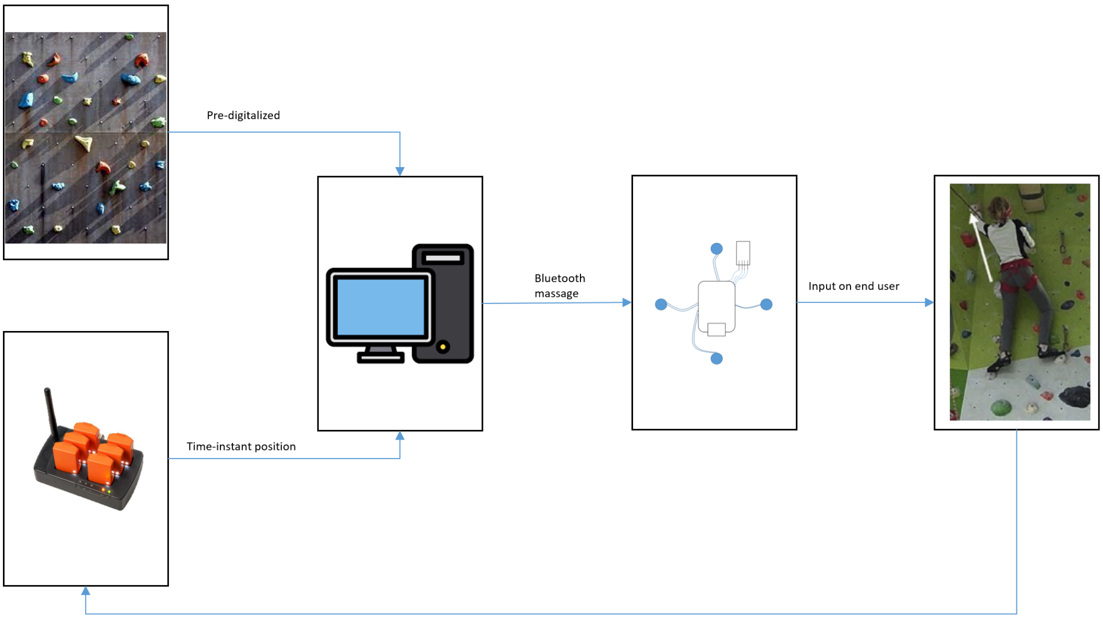


Figure 3.3: Workflow of the prototype. From left to right: Up) the climbing wall and its different routes are digitalized and saved on PC, image from [12]; Down) the Awinda Xsens tracking sensor send wireless data about the position of the limbs of the user to a pc, image from [10]; the pc compares the limb positions and the digitalized map then it sends a string of 8 characters to the seeduino-xiao microcontroller by Bluetooth; the microcontroller starts to vibrate on the skin of the end user guiding them to the next hold with the correct limb

3.3 Development of the prototype

3.3.1 First step

The first step is to develop the single unit able to receive the Bluetooth message from a Matlab script and be able to send a distinctive input direction to the arm of the user.

The end result can be seen in figure [9]. It is composed by a Seeduino-Xiao microcontroller, a Bluetooth 5.0 (Ble) module "DSD Tech Hm-19", a lithium-polymer battery (Lipo) of 3.7V 1100mAh, 4 vibrating motors model "Vikyezw965gbsri" and a switch. The Bluetooth module is connected to the microcontroller from Vcc, Gnd, Trasmitted data TxD, Recived Data RxD to respectively pin 3.3 V, Gnd, pin 7 RxD and pin 6 TxD. The vibrating motors are connected to pins: 4 (up),3 (right),8 (down),9 (left) by a 27-30 cm wires and they are powered up by an analog output of 3.3V. The length of the wires is decided to easly position them both on the wrist of a person and on the back of a person (for future testing). The Seeduino Xiao microcontroller is chosen because is one of the smaller (20x17.5x3.5 mm, [21]) and cheap ones with enough pin, able to supply each output pin with 3.3V. The motors are chosen because small enough (diameter 8 mm and high 3 mm) and are able to vibrate to 2500 rpm (around 40 Hz). This frequency is able to be perceived from the user. The BLE is chosen because is low energy consumption and because the "Hm-19" has a long range of communication (they claim 100 m range in open space more than enough).

Figure 3.4: First bracelet prototype

The Seeduino was programmed using Arduino IDE (integrated development environment). The SoftwareSerial.h library is used to enable a serial communication on pin 6 and 7. The message is in byte with this structure:

115
from 0 to 255
from 0 to 255
from 0 to 255
from 0 to 255
90

Where the first byte is 115; it is used to communicate to the smart wristband that the message is starting.90 is used to communicate the end of the message.

The message is sent from Pc using Matlab 2019b. After the central Pc advertises and scans for the peripheral if it establishes the connection it send the previous described message to the characteristic "FFE1" in "FFE0" Service (we choose to change only the name of the Bluetooth module and not the characteristics and service name just because in the future part of development I will need to differentiate only to witch BLE module the Pc connects but all BLE module will receive similar commands to the same characteristic).

The first prototype is installed on the right wrist: stretching out the arm so that the palm of the hand is facing the ground the vibrating motor 3 will be positioned as much as possible in contact on radios, the motor 9 on ulna, motor 4 on the upside of the wrist and motor 8 in the downside; microcontroller, battery and BLE module will be positioned between the elbow and the wrist(the position are chosen to be best perceived according to results on [17] and [18]). All components of this single unit are fixed using non-magnetic tapes for athletes (3.5).

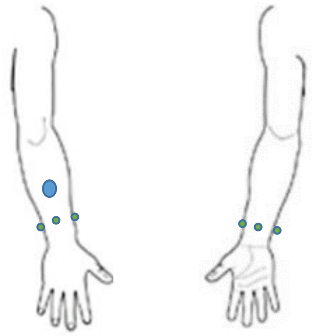


Figure 3.5: Visual description of the different components of the wristband on the right wrist; green dots are used to report the positions of vibrating motors, blue dots to report where are stacked other components.

In Chapter 4, Test 1 gives good results in guiding the testers in a very responsive and reliable way (as expected, as shown in Chapter 2,because there are many example of guiding using haptic interfaces for example: [4], [14], [15]). It passes to the next phase of prototyping.

3.3.2 Second step

The second step of development is an integration between the Xsens technology with the haptic stimuli, to be able to guide the blind subject to a given grapple in a virtual map.

In previous development phase, the hardware was integrated with the Xsens Awinda. Awinda is a pack of 17 wireless motion trackers (MTw) and body straps, used to connect them to the body. Data is transmitted wirelessly between each MTw and the so-called Awinda Station using a patented protocol. The size of a MTw are 47 mm x 30 mm x 13 mm and it weighs 20 g. Each MTw unit has 3D gyroscopes, 3D accelerometers, 3D magnetometers a battery and a transceiver [6]. The battery life advised of MVN Awinda is 6 hours, but usually is less because the system stops tracking if one of the 17 MTw units is not connected to the Awinda station (however it is feasible for this application because the training session for climbing lasts 1-2h).

Figure 3.6: Example of Xsens Awinda on a user from [6].

The wristband developed previously, thanks to the small dimension of components, is positioned between the MTw of the right hand and MTw on the arm as was intended in the previous phase.

Before explaining the software, it is necessary to demonstrate the model and the assumption used. We can model the climb wall as a series of 2D plan with different orientation in the space.

Each plan, with different orientation, is modelled as a matrix z1y1 containing, in each cell for every millimetre of the wall, a positive value, if in that position exists a hold (the value of the number determinate the range colour of the hold and so at witch route it belongs).

So fixed the 0 frame in the real map, each hands and feet positions will be represented in a roto-translated reference frame of that portion of the wall. The pose in the frame of the wall can be computed using formulas from [5]:

$$p^1 = A_0^1 * p^0 = (A_1^0)^{-1} * p^0 \tag{3.1}$$

$$\boldsymbol{A}_0^1 = \begin{bmatrix} \boldsymbol{R}_1^{0T} & -\boldsymbol{R}_1^{0T}\boldsymbol{o}_1^0 \\ \boldsymbol{0}^T & 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{R}_0^1 & -\boldsymbol{R}_0^1\boldsymbol{o}_1^0 \\ \boldsymbol{0}^T & 1 \end{bmatrix},$$

As an assumption we think that the movement is only in a vertical route, so we don't consider the moment along the x axis. The wall(of the route) is mobilized as 5000x5000 mm map with the origin of reference 1 in position y=0, z=5000 of reference 0 and rotated by a matrix

$$R_1^0 = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1. \end{bmatrix}$$

The Xsens reference system is computed after a calibration. It is always in the right heel of the user according to [6]: "X positive when moving forward, and lying in the horizontal plane. This axis is defined by the user during subject calibration. Y pointing lateral, and orthogonal to X and Z according to the right-handed coordinate system. Z along the vertical, gravity referenced, positive when pointing up." During calibration the user must give the back to the climb wall. An assumption is that in the building structure the floor is perpendicular to its wall. After calibration it is important to manually save the position of the origin of Xsens reference frame in the 0 reference frame (origin of Xsens reference frame is the starting position of the right heel).

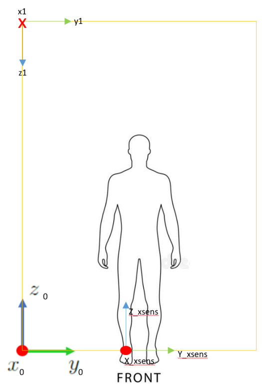


Figure 3.7: Reference frames used during computation: the transformation matrix A_1^{xsens}

A_1^{xsens} is computed as:

$$A_1^{xsens} = A_0^{xsens} * A_1^0 = \begin{bmatrix} 1 & 0 & 0 & -x_{xsens} \\ 0 & 1 & 0 & -y_{xsens} \\ 0 & 0 & 1 & -z_{xsens} \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 5000 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 & -x_{xsens} \\ 0 & 1 & 0 & -y_{xsens} \\ 0 & 0 & -1 & -z_{xsens} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

In this step a fake virtual map is created randomizing the position of 4 different dimension ovals (previously painted on paint) to simulate the holds. The program assigns to each grapple different random colours. The oval-holds are put in the map randomly using the grid in figure 3.8(it is a typical grid that hold shops advise to use for indoor climbing). So the positions where the ovals can be fitted are in a staggered grid with distance 25 cm between each other.

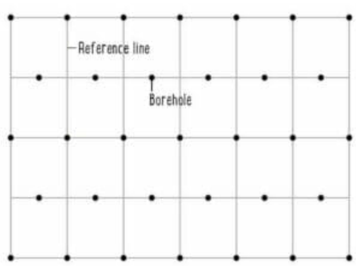


Figure 3.8: This is a typical pattern called the staggered grid(from [16]). First hole of each even row is in the middle between the first and second hole of the previous row. Typically, every hole has 15-25 cm distance from the previous one. And every row is vertically spaced apart by the same distance. Resulting in 18-50 holes/m2

One of the many random maps created can be seen in figure 3.9:

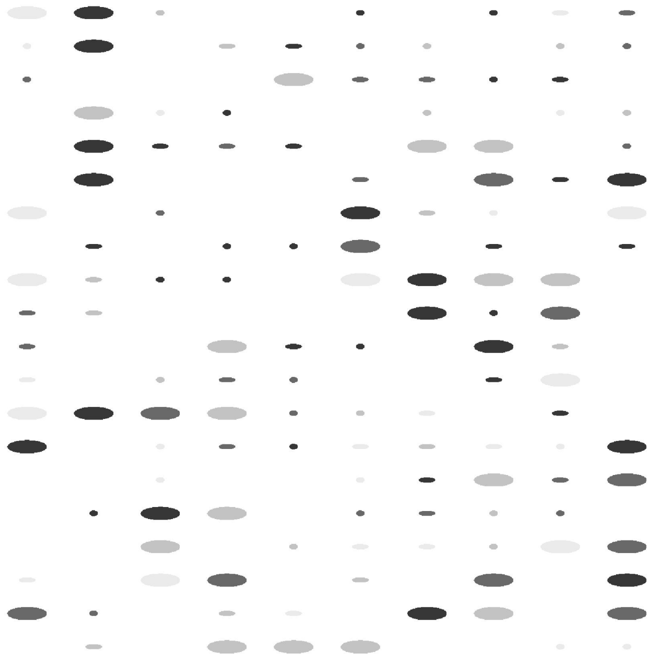


Figure 3.9: One of the random generated maps

Xsens Awinda sends to its licensed software MVN the data from its unit and MVN elaborates them. Xsens Awinda is able to stream data to 60 Hz frequency, so after a quick conversation about the position and orientation every 16.7 ms. MVN can stream data to a Matlab file using a provided API, or save the message in a .mat file to analyze the program in a second moment. Since the Xsens equipment is in Siena I work with data provided by the professors involved with the prototype. The Awinda technology is able to stream different kinds of messages, each with different information. The type of message chosen for streaming is M X T P 0 2: absolute position and orientation using quaternion. Each message is formed by 24 byte of metadata that contains various data such as the type of the message, message id, data counter and so on. The more important bytes in this message are the bytes 13:16 that gives as the time code of that message (MVN Analyze/Animate contains a clock which starts running at the start of a recording. The clock measures the elapsed time in milliseconds. Whenever new captured data is sampled the current value of the clock is sampled and saved in these bytes [9]). Then for each segment (23) of the Xsens body model it sends 32 bytes. The right hand is classified as the 11th body part(see figure 3.10).

So, the total bytes for message MXTP02 are 24+23x32=760. The data regarding the position of the right hand are the following ones in each message:

1. 10*32+4+25:28=349:352 (bytes of the messages for coordinate X of the right hand)
2. 10*32+8+25:28=353:356 (bytes of the messages for coordinate Y of the right hand)
3. 10*32+12+25:28=357:360 (bytes of the messages for coordinate Z of the right hand)

In a Matlab file we upload the virtual map, from pc the user is able to decide which route (colour of holds) to follow.

Segment Name	Segment Index
Pelvis	0
L5	1
L3	2
T12	3
T8	4
Neck	5
Head	6
Right Shoulder	7
Right Upper Arm	8
Right Forearm	9
Right Hand	10
Left Shoulder	11
Left Upper Arm	12
Left Forearm	13
Left Hand	14
Right Upper Leg	15
Right Lower Leg	16
Right Foot	17
Right Toe	18
Left Upper Leg	19
Left Lower Leg	20
Left Foot	21
Left Toe	22
Prop1	24
Prop2	25
Prop3	26
Prop4	27

Figure 3.10: Xsens classification for each body part; it is based on a 0-based index; Matlab is 1-based index so add 1 to each segment index. [9]

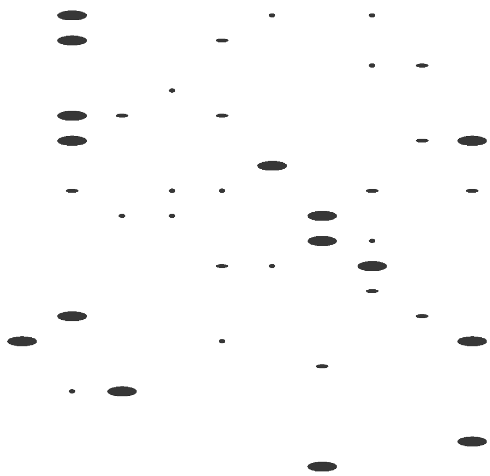


Figure 3.11: Visual representation of selected route from figure 3.9, in this matrix correct hold are saved as 1, if there is no correct hold that position is saved as 0.

Using the previous considerations, the Matlab file receives for each time instant, the positions tracked with Xsens, roto-traslate them in the from xsens reference frame to 1 frame of the 2D plane and confronts them with the matrix containing only the data of the chosen route. Then it checks if there is a hold in a rectangular check area (of dimension 1 times the shoulder-wrist length and as height 1/2 length between shoulder and wrist) centred in the hand. If the program finds a hold in that area, it sends via Bluetooth a command of 6 bytes to the unit developed, to let its motor vibrate in order to reach the corresponding hold (so via haptic stimuli it gives the commands up, down, left, right, up-left, up-right ,down-left, down-right vibrating with the corresponding motor/s). When the centre of the hand is around 5 cm (adjustable by the program) from the hold it stops vibrates. If the hand is already on a hold the program starts scanning again the map until it finds a new viable hold higher than the previous point in the map. If it finds a new hold with these features, it starts guiding the user towards the new hold. If the program doesn't find a new viable hold, it keeps all the vibrating motors shut if the hand is around 5 cm from the current hold, but if the hand moves away from the current hold and the program scanning doesn't find a new hold, the program starts the vibrating motors to guide back the hand towards the same hold. With these methods, by moving hand, the user can search new higher hold to follow the route with and the program will guide him towards them.

For the stream we used a UDP (User Datagram Protocol) connection to the MNV software through the port 97663 as suggested by the manual. UDP connection was made thanks to the Matlab feature "judp" provided by Xsens manufacturers in the developer kit [10]. The choice of a UDP connection instead of a TCP (Transmission Control Protocol) one was made because of the quickness of information transfer (a late information about the streaming of the position is useless and can give wrong inputs and a wrong guidance). In 3.12 there are some pictures of how the program works out:

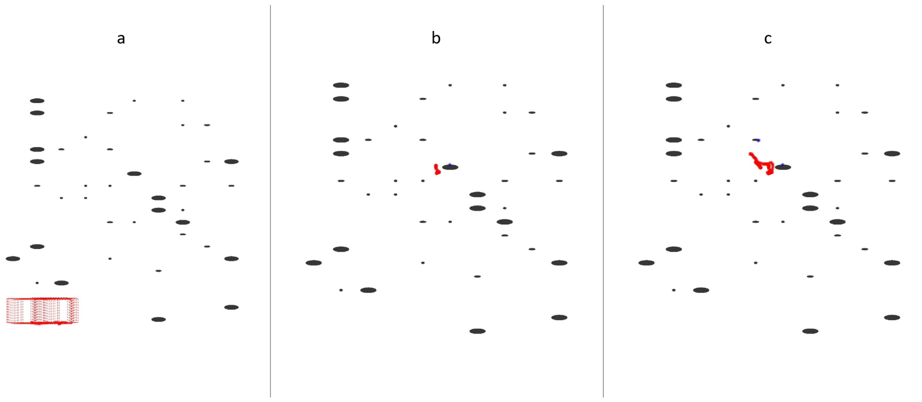


Figure 3.12: In this pilot the haptic device was installed on the left hand of the user (his dominant hand).In a. it is highlighted the rectangular search area: the program doesn't find any reachable hold so the haptic device motors don't vibrate. In b. the user is already near a hold(*): the haptic device guides him "up-right". When the device is near the blue dot it stop. Now it doesn't find any new hold in the reachable area so no motor vibrate. Then the user decides to move the hand to search a new hold. During the search the device points to "down-right" so to the last reachable hold remembered. In c. the program finds a new reachable hold so in this moment it vibrate pointing to "up-right"

The pilot is a success. It proves that the program works and moreover, the device hardware doesn't interfere with the positioning of the xsens on the body. The motor vibration doesn't affect much the tracking of Xsens; sometimes the user, who completed the pilot, pointed out has difficulty perceiving the difference between the up-right and the up while clearly perceiving the up-right and up-left changes and the likes.

3.3.3 Third step

In part 3 of the development, 3 more units are created identical to the first one. At first it is thought to distribute 1 per limb. During this phase of the project it was thought if other configurations will be useful. The following 3 configurations have thought:

1. Distributed one: the haptic guidance interface is composed of 4 devices (all independent from each other) on each limb. Each device has 4 vibrating motors. A Pc steers the climber controlling the 4 devices. Each limb is guided one at a time (same for the next 2 configuration). 4 motors of the haptic device on the correspond limb vibrate according to a policy to guide the climber. The possible directions are up, right, left, down, up-left, up-right, down-left, down-right (same for the next 2 configurations).

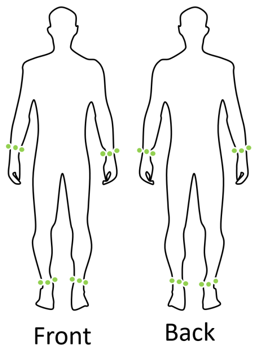


Figure 3.13: Distributed configuration: vibrating motors position.

2. Localized one: one haptic device is located in only one loco; from experiment in Chapter 4 the best loco is on the wrist of the dominant hand. So on the wrist there are 4 motors that vibrate to steer the limbs of the climber. To indicate witch limb needs to move, another Seeduino is positioned on the back. It is connected to 3 motors, each on: the other arm, on right leg and on the left leg. If the program wants to guide the climber dominant hand: only the first 4 motors, on the dominant wrist, vibrate according to the guidance policy. If the program tries to guide another climber's limb: The 4 motors on the wrist vibrate according to the decided policy; at the same time one of the other 3 motors vibrates on the corresponding limb.

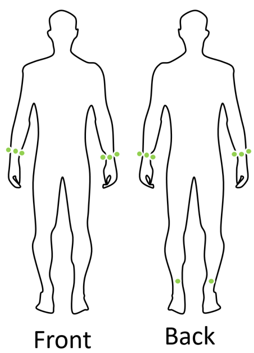


Figure 3.14: Localized configuration: vibrating motors position.

3. Hybrid one: 3 haptic devices are used. One device is in each wrist with 4 vibrating motors. A third device is on the back. It is connected only to 2 vibrating motors: one on the right leg and the other on the left leg. The arms guidance is the same of the distributed case (guidance only on the corresponding arm to move). In case of guiding the left or right leg: the motor on the corresponding leg vibrates; at the same time the 4 vibrating motors of the left or right wrist vibrate) to guide the corresponding leg.

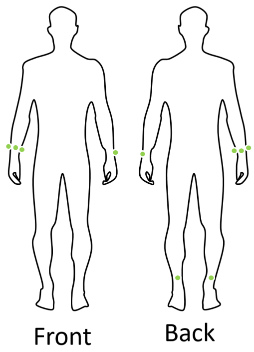


Figure 3.15: Hybrid configuration: vibrating motors position.

Another decision is to decide which policy is the best to guide the climber. The 2 main policy are selected, "Continuous" policy and "Alter" one:

1. "Continuous": If the limb needs to move to the corresponding direction; the corresponding motor vibrates at maximum pwm until it receives the command to stop.

2. "Alter": the motors will vibrate for 0.5s at maximum pwm and then will stop for 0.5 s and so on until a new command issue is send to the haptic device.

From the test results in Chapter 4 it is thought that best configuration is: Distributed configuration with alter policy. The policy is chosen due to results on Chapter 4, where it can be seen that in most cases the alter policy is equal or better perceived from the study subjects than the continuous one.

The distributed one is chosen due to its simplicity to be understand by the final user. Indeed, in this case the climber needs to perceive only 1 or 2 motors vibrating on the same time. In the other case could need to perceive 3 motors on the body on the same time. The distributed one is the configuration with more hardware, but it is the one more easily perceived by the user and the one with less mental effort by the user (less mental error = less error from the user).

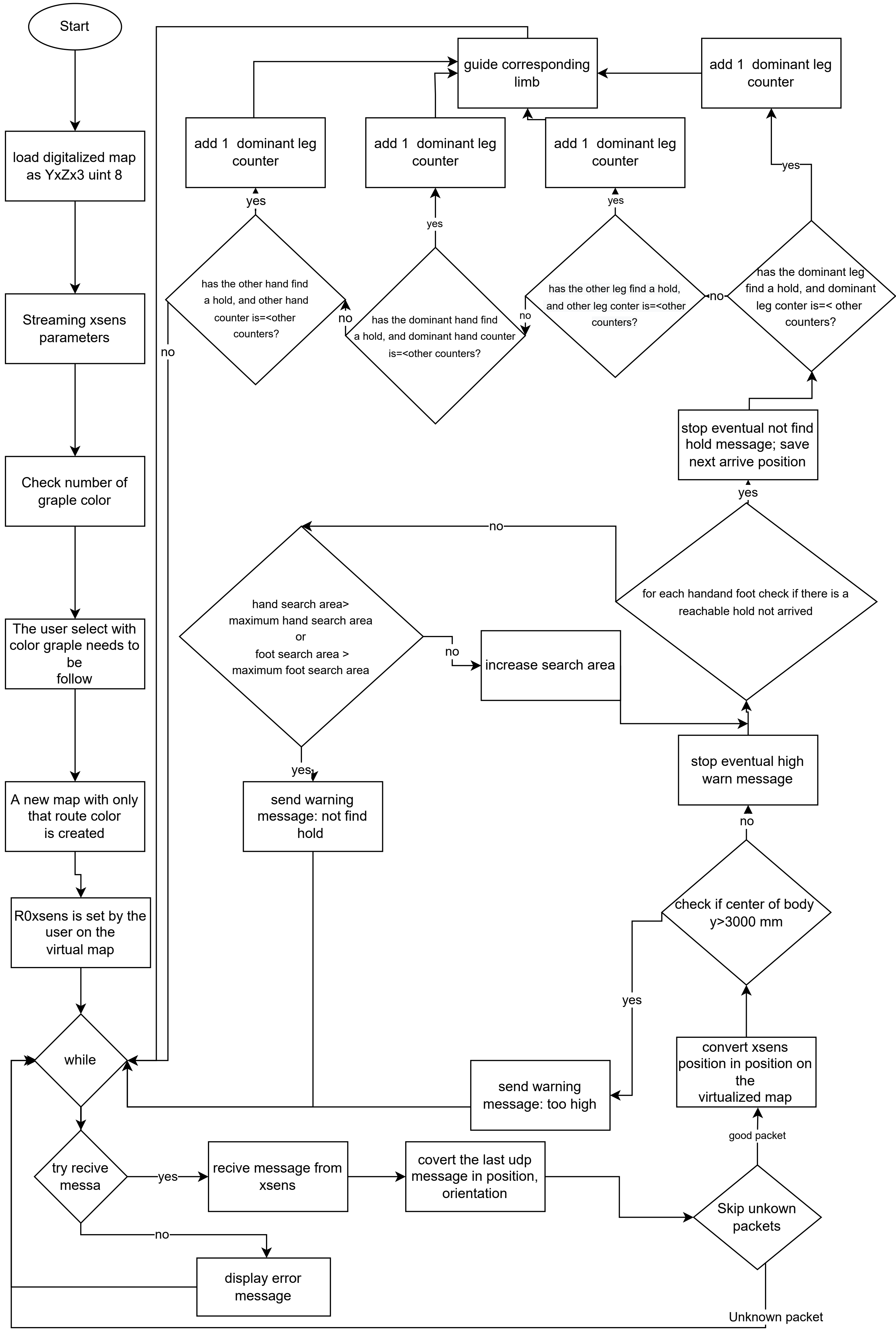
For example, we want to guide the left leg of a right handed user to a foothold on up-right position. In case 1 the user needs to correctly perceive vibrating motors on left leg "up" and the vibrating motor on left leg "right": it is intuitive to move the left leg on up-right. In case 2: the user needs to perceive the left leg motor, the "up" motor on the right wrist and the "right" motor on the right wrist. In case 3 he needs to perceive left leg motor, "up" motor on the left wrist and the "right" motor on the left wrist.(So in these cases, the localized configuration and the hybrid one add another layer of abstraction to the user).

3.3.4 Fourth step

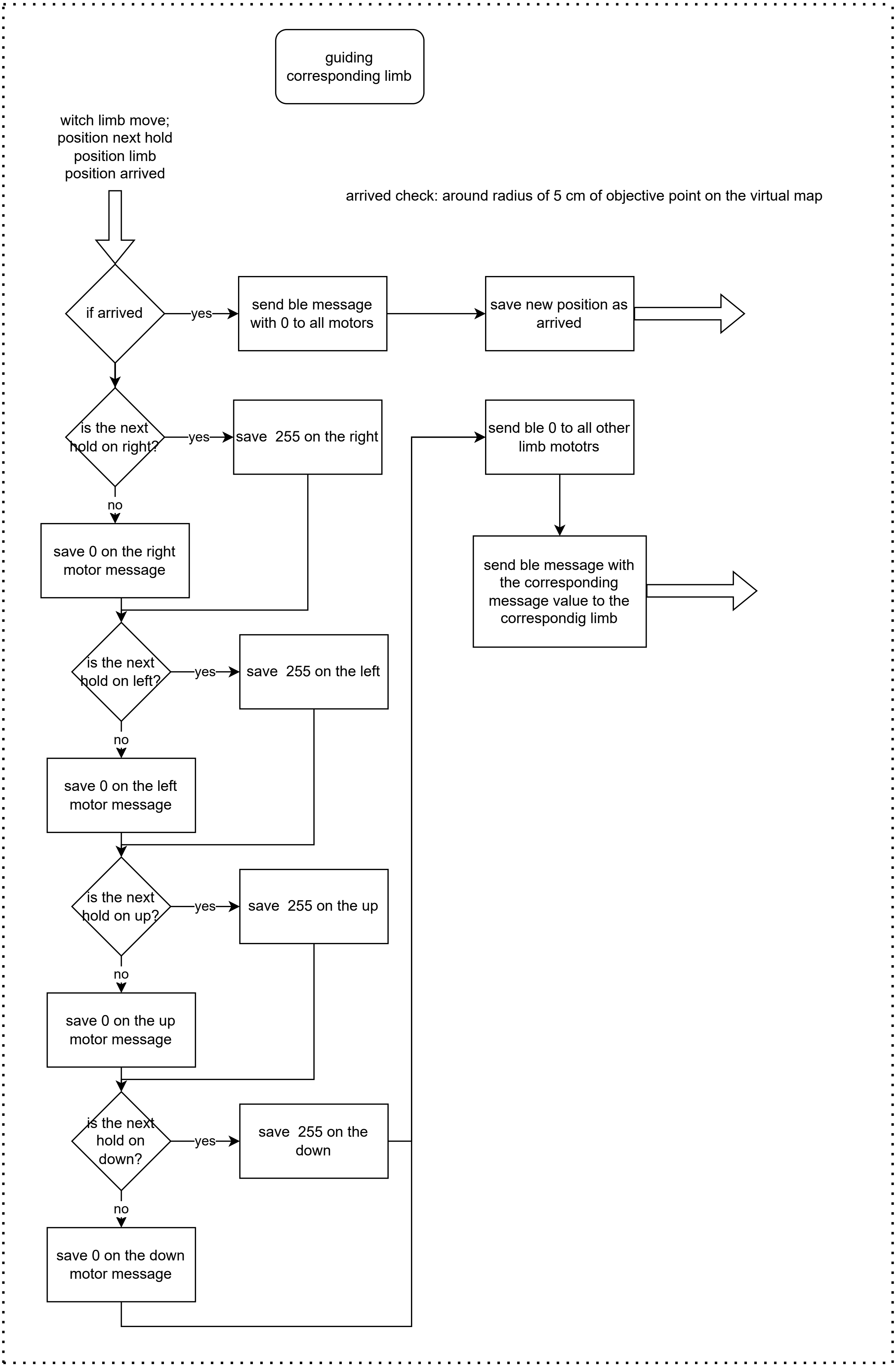
Basically the program remains the same as in phase 2 and 3, but the matlab file looks for the presence of a possible foothold in a semicircular area of radius 25 cm from each end of the limb. If it finds more than one possible foothold, it gives priority to guide first a leg and then a hand (priority to the dominant ones and making all the limbs move at least once). If it does not find anything, increase the search area by 5 cm up to a maximum of 50 cm away from the foot and 30 cm from the hand. If it still does not find anything, it signals through a double vibration in all motors with a distance of 1.5 seconds. If Bluetooth connection is lost from more than 5 seconds the haptic device starts to vibrate continuously for 5 seconds with all 4 vibrating motors together before stopping vibrating. If the athlete exceeds the maximum safety height with the center of his body, all the motors of all the haptic device begin to vibrate turning off and turning on every 0.5 seconds to signal the danger until the center of his body is in a safety high (less than 3 m). The structure of the Matlab code is in the diagram in the following page. The message used to communicate to the haptic device is the following one:

115
from 0 to 255
from 0 to 255
from 0 to 255
from 0 to 255
0 or 1
0 or 1
90

The message is similar to the one of the first step. 115 is used to let the smart wristband know that the message is starting from the computer and 90 is used to communicate the end of the message. Cell 2 to 4 are to control in pwm the vibration of the motors. 255 is 100%. Seeduino timer is used to start and stop the motor about every 0.5 seconds. Cell 5 is for attention message too high and cell 6 for attention message if don't find any reachable hold around every limb.



Start
load digitalized map as YxZx3 uint 8
Streaming xsens parameters
Check number of graple color
The user select with color graple needs to be follow
A new map with only that route color is created
R0xsens is set by the user on the virtual map
while
try recive messa
yes
recive message from xsens
covert the last udp message in position, orientation
Skip unkown packets
Unknown packet
good packet
no
display error message
convert xsens position in position on the virtualized map
check if center of body y>3000 mm
yes
send warning message: too high
no
stop eventual high warn message
for each handand foot check if there is a reachable hold not arrived
no
hand search area> maximum hand search area or foot search area > maximum foot search area
no
increase search area
yes
send warning message: not find hold
yes
stop eventual not find hold message; save next arrive position
has the dominant leg find a hold, and dominant leg conter is=< other counters?
yes
add 1 dominant leg counter
no
has the other leg find a hold, and other leg conter is=<other counters?
yes
add 1 dominant leg counter
no
has the dominant hand find a hold, and dominant hand counter is=<other counters?
yes
add 1 dominant leg counter
no
has the other hand find a hold, and other hand counter is=<other counters?
yes
add 1 dominant leg counter
no
guide corresponding limb


guiding corresponding limb
witch limb move;
position next hold
position limb
position arrived
arrived check: around radius of 5 cm of objective point on the virtual map
if arrived
yes
send ble message with 0 to all motors
save new position as arrived
is the next hold on right?
yes
save 255 on the right
no
save 0 on the right motor message
send ble 0 to all other limb mototrs
send ble message with the corresponding message value to the correspondig limb
is the next hold on left?
yes
save 255 on the left
no
save 0 on the left motor message
is the next hold on up?
yes
save 255 on the up
no
save 0 on the up motor message
is the next hold on down?
yes
save 255 on the down
no
save 0 on the down motor message

Chapter 4

Experiments

We conducted several tests to study users' perception of the haptic stimuli and to better position the vibrating motors on the body of the climbers.

4.1 Experiment 1

The aim of this test is to collect some data on the perception rate of haptic stimuli in the wrist. The hardware used in this test is the one presented in Chapter 3 first step of prototyping.

4.1.1 Participants and task

Nine young people of different age (span from 17 to 19 years old) participated in the experiment. No one of the participants have been previously in contact with a wrist haptic device for guidance. Every one of them is not visual impaired. No one of them uses in daily life a smartwatch or a smart-band. Eight of the participants are right handed.; the participant 8 is the only one left handed. The prototype in each participant is located in the right hand. Furthermore, the height (mean=171.3 cm, standard deviation=9.67 cm), the weight (m=77 Kg, sd=12.23 Kg) and the BMI (body mass index) (m=21,78, sd=3,01) is measured. Of the nine participants only 2,3,4,5 and 8 practice sports more than 2 times a week. To build a set of data the participants are asked to stand while blindfolded and wearing the device. Then they are asked to choose between 5 options: up, down, right, left, off depending on the perceived stimulus. A program sends 25 five BLE messages to the wristband. Each message contains the information of which motor should be activated. The messages order is randomized. However, each tester will receive 5 messages each for up, down, right, left, off. The participants don't know how many messages of each type will be sent to them. They are not aware of the total number of messages sent. An operator is in charge of collecting the response of the participants.

4.1.2 Procedure

To assess the data set, the following procedure is performed for each participant. First the participant wears the wristband. Then he is blindfolded. he stands up. The operator will start a routine to test if all the motors are well positioned and if they work correctly. At this time the operator sends a message to vibrate the motors in order (up, right, down, left), saying witch one of them is moving, for about 5 s in order to give to the participant a brief first experience of the haptic stimuli. Then the operator moves aside from the participant giving him is back. Then the operator communicates to the participant that the test is about to start. After starting the test, a routine will send vibration haptic stimuli to the participant every 3 seconds. After each time the message is sent, a message shows up on the computer of the operator saying him to collect the current choice of the participant. To the participant is asked to repeat until the end of the experiment the current stimuli received (so during the 3 second they repeat more times the same instruction received, the operator saves only one instruction the moment it receives the command from the routine). After the end of the experiment, the 25 messages send to the participant, are saved in a txt file. Then the operator will take them and compare then with the one that he saved during the experiment. All the experiment is video-audio recorded. The record is used to check if the operator reports correctly the message received from the participants. Each experiment from start of the procedure to end is about 10 minutes.

4.1.3 Results

The result of the experiment can be seen in Table 4.1:

Table 4.1: Wrist 4 motors test

	Correctly perceived	Wrongly perceived	height (m)	weight (kg)	BMI	sport
test 1	23	2	1,88	77	40,95745	
test 2	24	1	1,74	70	40,22989	x
test 3	25	0	1,6	55	34,375	x
test 4	23	2	1,8	77	42,77778	x
test 5	25	0	1,65	57	34,54545	x
test 6	24	1	1,57	59	37,57962	
test 7	25	0	1,72	71	41,27907	
test 8	22	3	1,73	73	42,19653	x
test 9	25	0	1,73	94	54,33526	

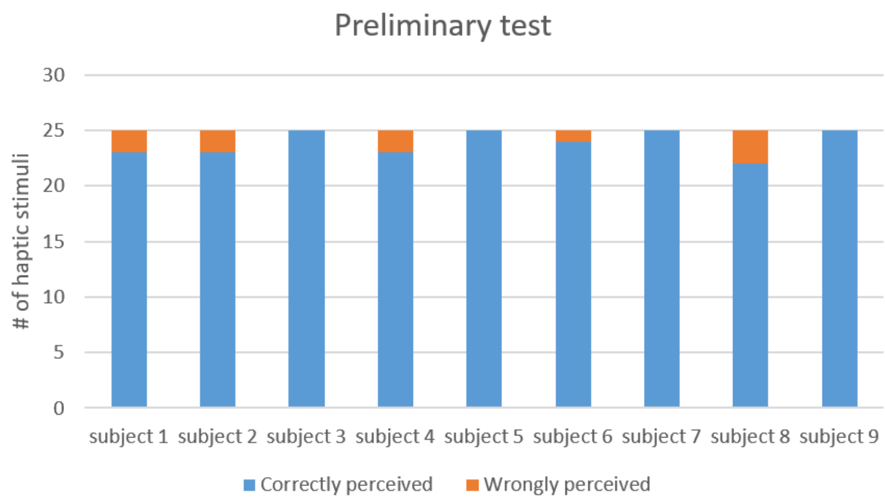


Figure 4.1: Diagram of haptic response on the preliminary test

As it can be seen, the results are very encouraging to continue develop the system. Note: as stated in [17] the movement will decrease the detection rate. In this test we have a detection rate of 96 %. The one with the worst perception rate is participant 8, maybe due to the fact that the wristband is not on his dominant hand. Removing 8 from data set we have a detection rate of 97 %. These are good results because the participants have only 3 seconds to receive the message, determinate which is the vibrating motor and says the relative position. Every participant is able to say properly when all motors are off. Removing from the data-set the off condition, we have a right detection rate of 95 % and the results can be seen in 4.2 diagram.

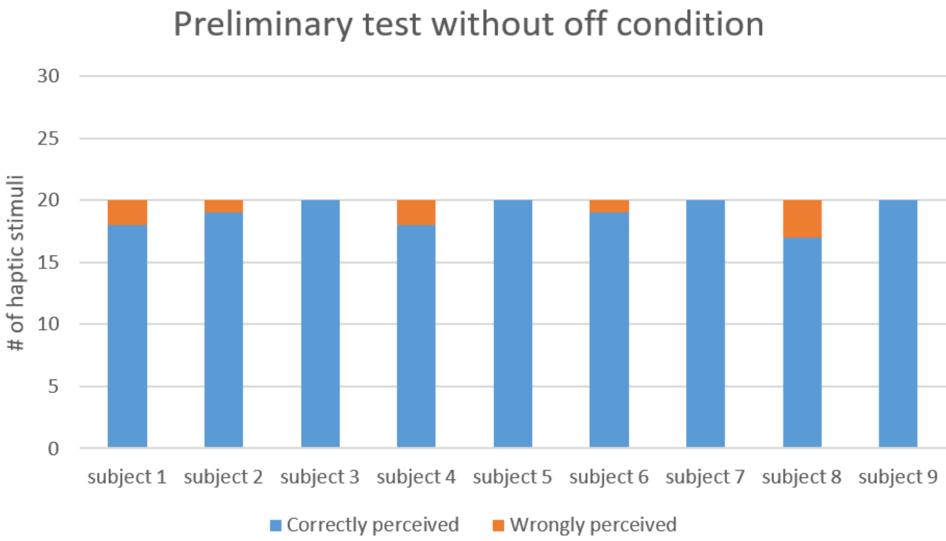


Figure 4.2: Diagram of haptic response on the preliminary test without off condition

4.2 Pilot of the system

A study of the system, developed in step 2 of Chapter 3 (integration of the Xsens Awinda with the haptic wrist device for guidance), is conducted in at the University of Siena. The guidance during the pilot works as intended. We test different levels of vibration of the mini motors. Works out that the best perception rate is when the motors vibrating at 200 Hz.

4.3 Experiment 2

The aim of this experiment is to individuate witch parts of the body are most suited for wearing the prototype developed in step 3 of Chapter 3. In particular, the participants will wear a single unit each time in a different body part of the following: wrist, ankle and spine. For each body part 4 identical test have been performed. We call the conducted tests with names indicating their characteristics: "Continuous5", "Alter5", "Continuous9" and "Alter9".

4.3.1 Test: Continuous5

Participants and task

Four young people of different age (span from 17 to 19 years old) participated in the experiment, different from the ones of the experiment 1. The participants are 2 males and 2 females. No one of the participants have been previously in contact with a wrist haptic device for guidance. Every one of them is not visual impaired. No one of them uses in daily life a smartwatch or a smartband. Every participant is right handed. The prototype in each participant is located on the right wrist (for the test concerning the wrist); on the right ankle (for the test concerning the ankle); on the spine (for the test concerning the spine). The participant takes a short break between each of these test. Furthermore, the height (mean=172 cm, sd=15.5), the weight (m=69.5 Kg, sd=15.09) and the BMI (body mass index) (m=23.36, sd=2.126) is measured. To build a set of data the participants are asked to stand while blindfolded and wearing the device. Then they are asked to choose between 5 options: up, down, right, left, off depending on the perceived stimulus. In this set of tests, the pattern of vibration is a continuous vibration in the corresponding mini motor for the corresponding time interval. A program sends 25 BLE messages to the corresponding haptic device. Each message contains the information of which motor activate. The messages order is randomized. However, each tester will receive 5 messages each for up, down, right, left, off. The participants don't know how many messages of each type will be sent to them. They are not aware of the total number of messages sent. An operator is in charge of collecting the response of the participants.

Procedure

To assess the data set, the following procedure is performed for each participant. First the participant wears the haptic device into the corresponding body part (wrist, ankle, back). Then he is blindfolded. he stands up. The operator will start a routine in order to test if all the motors are well positioned and if they work correctly. At this time the operator sends a message to vibrate the motors in order (up, right, down, left), saying witch one of them is moving, for about 5 s in order to give to the participant a brief first experience of the haptic stimuli. Then the operator moves aside from the participant giving him is back. Then the operator communicates to the participant that the test is about to start. After starting the test, a routine will send vibration haptic stimuli to the participant every 3 seconds. After each time the message is sent, a message shows up on the computer of the operator saying him to collect the current saying of the participant.

To the participant is asked to repeat until the end of the experiment the current stimuli received (so during the 3 second they repeat more times the same instruction received, the operator saves only one instruction the moment it receives the command from the routine). After the end of the experiment the 25 messages send to the participant are saved in a txt file. Then the operator will take them and compare then with the one that he saved during the experiment. All the experiment is video-audio recorded. The record is used to check if the operator reports correctly the message received from the participants. Each experiment from start of the procedure to end is about 10 minutes.

4.3.2 Test: Alter5

Participants and task

The participants are the same of the previous set of tests. The task is similar to the previous test but, instead of a continuous vibration pattern, one of the motors starts vibrate for 0.5 seconds than stops vibrate for 0.5 second and so on until a different command (up, down, right, left, off) is sent to them (typically for 3 second, but due to randomization can happen that the same message is sent 2 times in a row).

Procedure

Same of Test Continuous5. But using the vibration pattern described in Alter5: Participants and task.

4.3.3 Test: Continuous9

Participants and task

The participants are the same of the previous sets of tests. To build a set of data, the participants are asked to stand while blindfolded and wearing the device. Then they have to say one between "sopra, sotto, destra, sinistra, sopra-destra,sopra-sinistra,sotto-destra,sotto-sinistra,spento" (up, down, right, left, up-left, up-right, down-right, down-left, off), if the corresponding motor vibrates. In this set of tests, the pattern of vibration is a continuous vibration as in Test: Continuous5. A program sends 45 BLE messages to the haptic device. Each message contains the information of which motor activate. The messages order is randomized. However, each tester will receive 5 messages for each up, down, right, left, up-left, up-right, down-right, down-left, off. The participants don't know how many messages of each type will be sent to them. They are not aware of the total number of messages sent. An operator is in charge of collecting the response of the participants.

Procedure

Similar to Test Continuous5. However, this time the operator sends a message to vibrate the motors in order (up, down, right, left, up-left, up-right, down-right, down-left, off), saying witch one of them is moving, for about 5 s in order to give to the participant a brief first experience of the haptic stimuli. Then the operator moves aside from the participant giving him is back. Then the operator says that it will start the test. After starting the test, a routine will send vibration haptic stimuli to the participant every 3 seconds. After each time the message is sent, a message shows up on the computer of the operator saying him to collect the current saying of the participant. To the participant is asked to repeat until the end of the experiment the current stimuli received (so during the 3 second they repeat more times the same instruction received, the operator save only one instruction the moment it receives the command from the routine). After the end of the experiment, the 45 messages send to the participant are saved in a txt file. Then the operator will take them and compare then with the one that he saved during the experiment. All the experiment is video-audio recorded. The record is used to check if the operator reports correctly the message received from the participants. Each experiment from start of the procedure to end is about 15 minutes.

4.3.4 Test: Alter9

Participants and task

The participants are the same of the previous set of tests. The task is similar to test Alter5 (vibration alternated) but, the commands sends are from the set between up, down, right, left, up-left, up-right, down-right, down-left, off. So now the program sends 45 BLE messages to the haptic device. Each message contains the information of which motor activate. The messages order is randomized. However, each tester will receive 5 messages for each up, down, right, left, up-left, up-right, down-right, down-left, off. The participants don't know how many messages of each type will be sent to them. They are not aware of the total number of messages sent. An operator is in charge of collecting the response of the participants.

Procedure

Same of Test Continuous9. But using the vibration pattern described in Alter9: Participants and task.

4.3.5 Results on wrist

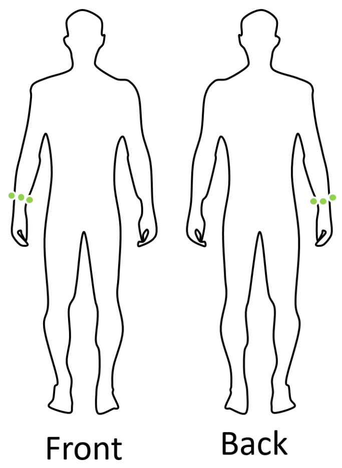


Figure 4.3: Motors of haptic device positioning on wrist

The result of the experiments Continuous5 and Alter5 can be seen in 4.2 table:

Table 4.2: Single vibration on wrist

		right	wrong
tester 1	Continuous5	20	5
	Alter5	23	2
tester 2	Continuous5	25	0
	Alter5	25	0
tester 3	Continuous5	25	0
	Alter5	25	0
tester 4	Continuous5	25	0
	Alter5	25	0

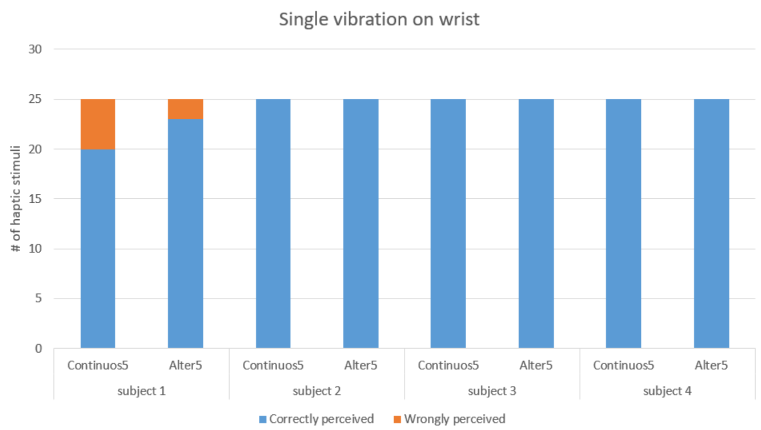


Figure 4.4: Diagram of haptic response of test Continuous5 and Alter5 on wrist

The results are similar to the first test; It is predictable because test Continuous5 is pretty much the same test of the First test. In the test Continuous5 we have a right detection rate of

94,6 %. For the test alter5 we have a right detection rate of 98%. From this first set of test seems that the alternation vibrating pattern is better perceived. Every participant is able to say properly when all motors are off. Removing from the data set the off condition we have a right detection rate of 93,75 % (Continuous5) and 97,5% (Alter5); the results can be seen in 4.5 graph.

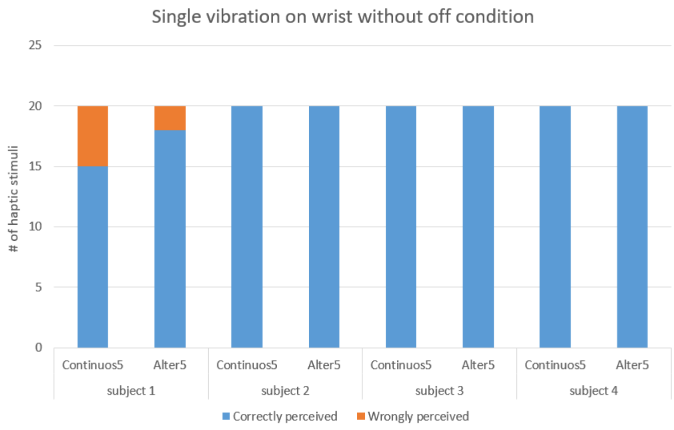


Figure 4.5: Diagram of haptic response of test Continuous5 and Alter5 without off condition on wrist

The result of the experiments Continuous9 and Alter9 can be seen in Table 4.3 Table:

Table 4.3: Single or double vibration on wrist

		right	wrong
tester 1	Continuous9	28	17
	Alter9	33	12
tester 2	Continuous9	31	14
	Alter9	34	11
tester 3	Continuous9	33	12
	Alter9	37	8
tester 4	Continuous9	30	15
	Alter9	40	5

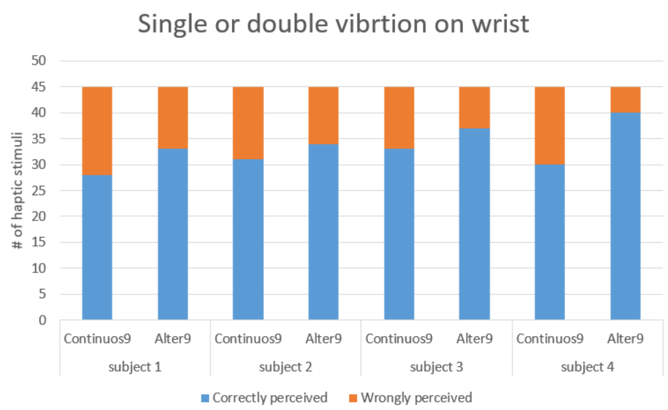


Figure 4.6: Diagram of haptic response of test Continuous9 and Alter9 on wrist

In the test Continuous9 we have a right detection rate of 67.7 %. For the test Alter9 we have a right detection rate of 80%. From this set of test, we understand that the alternating vibrating rate has a better right perception rate on the wrist. Every participant is able to say properly when all motors are off. Removing from the data set the off condition, we have a right detection rate of 63.25 % (Continuous9) and 77.5% (Alter9); the results can be seen in the graph 4.7.

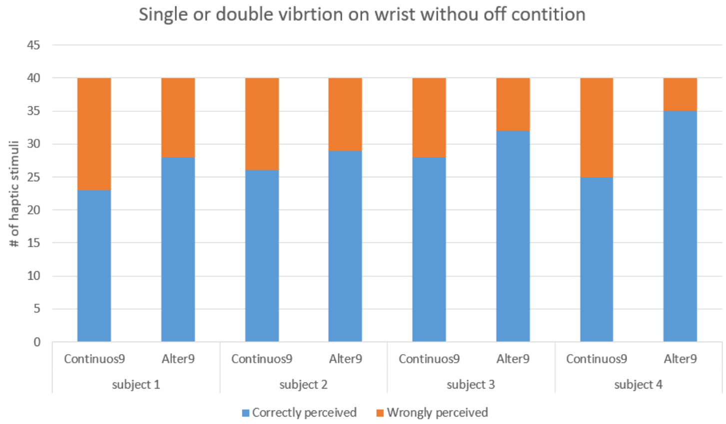


Figure 4.7: Diagram of haptic response of test Continuous9 and Alter9 on wrist

In Table 4.4 it is resumed all wrong perceived messages. Worth noticing that in case of wrong contemporary double vibration perception the subject are able in more than 90 % of the cases to feel only one of the two vibrating motors.

Table 4.4: Wrong message perception on wrist.

		up	down	right	left	up-right	up-left	down-left	down-right	off
tester 1	Continuous5	1	1	0	3	x	x	x	x	0
	Alter5	1	0	0	1	x	x	x	x	0
	Continuous9	1	1	0	0	1	5	5	4	0
	Alter9	0	1	1	2	3	4	1	0	0
tester 2	Continuous5	0	0	0	0	x	x	x	x	0
	Alter5	0	0	0	0	x	x	x	x	0
	Continuous9	1	1	2	2	2	2	2	2	0
	Alter9	0	0	1	1	2	3	1	3	0
tester 3	Continuous5	0	0	0	0	x	x	x	x	0
	Alter5	0	0	0	0	x	x	x	x	0
	Continuous9	0	0	1	0	2	3	3	3	0
	Alter9	0	0	0	0	2	1	1	4	0
tester 4	Continuous5	0	0	0	0	x	x	x	x	0
	Alter5	0	0	0	0	x	x	x	x	0
	Continuous9	2	1	1	1	2	2	3	3	0
	Alter9	1	0	0	0	1	2	0	1	0
		7	5	6	10	15	22	16	20	0

4.3.6 Results on ankle

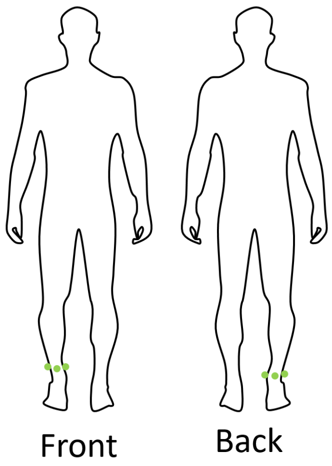


Figure 4.8: Motors of haptic device positioning on ankle

The result of the experiments Continuous5 and Alter5 can be seen in Table 4.5:

Table 4.5: Single vibration on ankle

		right	wrong
tester 1	Continuous5	25	0
	Alter5	23	2
tester 2	Continuous5	25	0
	Alter5	24	1
tester 3	Continuous5	20	5
	Alter5	19	6
tester 4	Continuous5	24	1
	Alter5	19	6

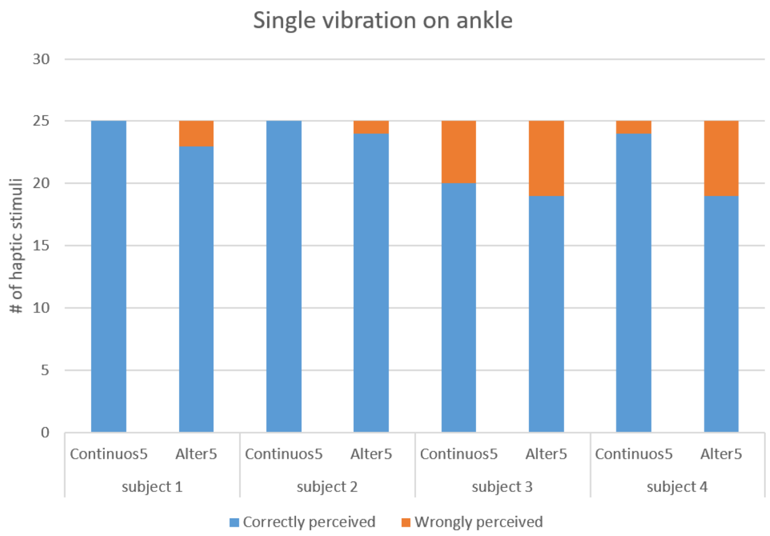


Figure 4.9: Diagram of haptic response of test Continuous5 and Alter5 on ankle

In the test Continuous5 we have a right detection rate of 94 %. For the test Alter5 we have a right detection rate of 85%. From this first set of test, it seems that the continuous vibrating pattern is better perceived on ankle. Every participant is able to say properly when all motors are off. Removing from the data set the off condition we have a right detection rate of 92.5 % (Continuous5) and 81.3 % (Alter5); the results can be seen in graph 4.10.

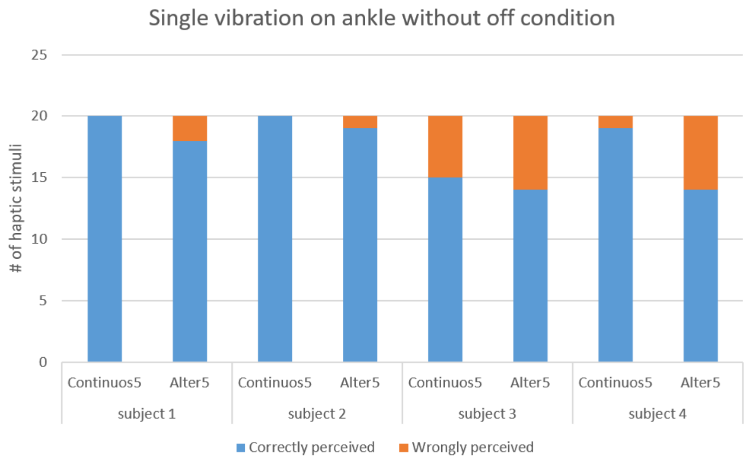


Figure 4.10: Diagram of haptic response of test Continuous5 and Alter5 without off condition on ankle

The result of the experiments Continuous9 and Alter9 can be seen in Table 4.6:

Table 4.6: Single or double vibration on anckle

		right	wrong
tester 1	Continuous9	28	17
	Alter9	26	19
tester 2	Continuous9	34	11
	Alter9	37	8
tester 3	Continuous9	30	15
	Alter9	38	7
tester 4	Continuous9	42	3
	Alter9	40	5

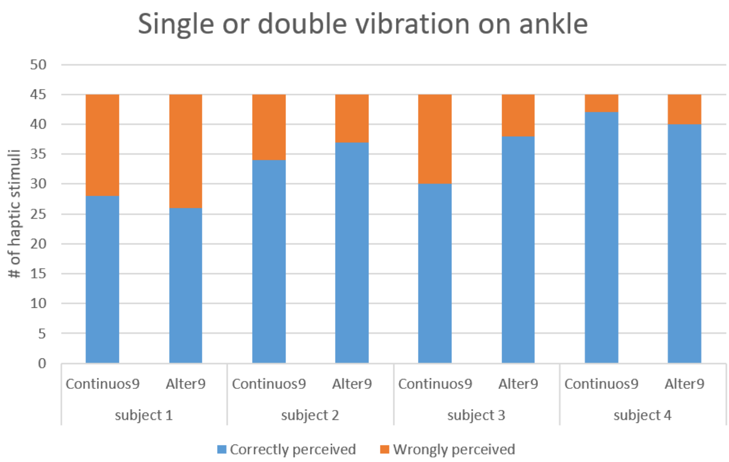


Figure 4.11: Diagram of haptic response of test Continuous9 and Alter9 on ankle

In the test Continuous9 we have a right detection rate of 74.4 %. For the test Alter9 we have a right detection rate of 78.3%. From this set of test, we understand that the alternating vibrating rate has a better right perception rate on the wrist. Every participant is able to say properly when all motors are off. Removing from the data set the off condition, we have a right detection rate of 71.25 % (Continuous5) and 75.6% (Alter5); the results can be seen in Graph 4.12.

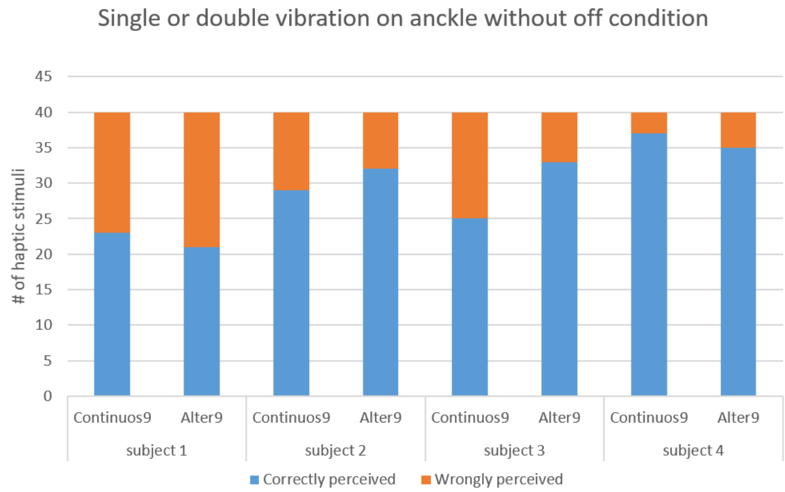


Figure 4.12: Diagram of haptic response of test Continuous9 and Alter9 without off condition on ankle

In Table 4.7 it is resumed all wrong perceived messages.

Table 4.7: Wrong message perception on ankle

		up	down	right	left	up-right	up-left	down-left	down-right	off
tester 1	Continuous5	0	0	0	0	x	x	x	x	0
	Alter5	0	2	0	0	x	x	x	x	0
	Continuous9	1	1	1	0	4	4	1	5	0
	Alter9	2	2	1	0	3	3	4	4	0
tester 2	Continuous5	0	0	0	0	x	x	x	x	0
	Alter5	0	0	0	1	x	x	x	x	0
	Continuous9	1	3	0	0	0	5	0	2	0
	Alter9	0	1	0	0	2	1	3	1	0
tester 3	Continuous5	3	0	1	1	x	x	x	x	0
	Alter5	3	2	1	0	x	x	x	x	0
	Continuous9	0	0	3	1	3	2	3	3	0
	Alter9	1	0	2	0	3	0	1	0	0
tester 4	Continuous5	0	0	1	0	x	x	x	x	0
	Alter5	0	1	2	3	x	x	x	x	0
	Continuous9	0	1	0	0	0	0	1	1	0
	Alter9	2	0	0	1	1	0	1	0	0

4.3.7 Results on back

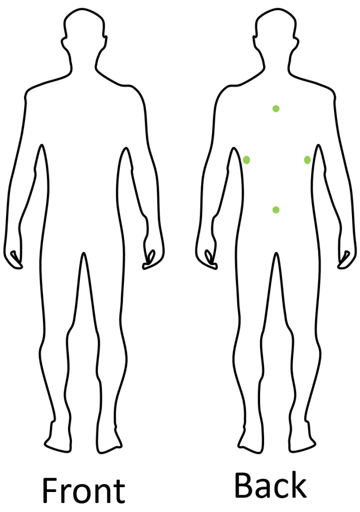


Figure 4.13: Motors of haptic device positioning on the back

The result of the experiments Continuous5 and Alter5 can be seen in Table 4.8:

Table 4.8: Single vibration on back

		right	wrong
tester 1	Continuous5	25	0
	Alter5	25	0
tester 2	Continuous5	23	2
	Alter5	24	1
tester 3	Continuous5	22	3
	Alter5	23	2
tester 4	Continuous5	23	2
	Alter5	23	2

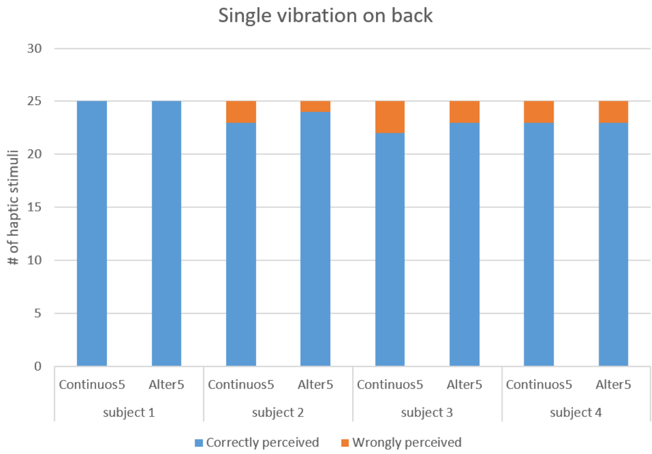


Figure 4.14: Diagram of haptic response of test Continuous5 and Alter 5 on back.

In the test Continuous5 we have a right detection rate of 93 %. For the test Alter5 we have a right detection rate of 95%. From this first set of test, it seems that the alternate vibrating pattern is better perceived on ankle. Every participant is able to say properly when all motors are off. Removing from the data set the off condition, we have a right detection rate of 91.25 % (Continuous5) and 93.75 % (Alter5); the results can be seen in Graph 4.15.

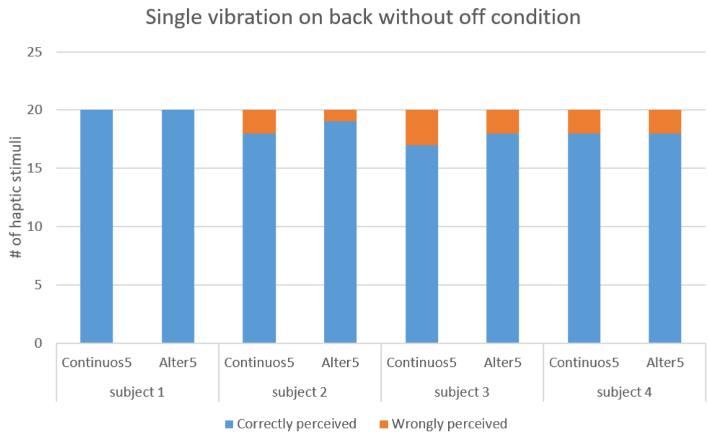


Figure 4.15: Diagram of haptic response of test Continuous5 and Alter5 on back without off condition.

The result of the experiments Continuous9 and Alter9 can be seen in Table 4.9:

Table 4.9: Single or double vibration on back

		right	wrong
tester 1	Continuous9	31	14
	Alter9	38	7
tester 2	Continuous9	28	17
	Alter9	34	11
tester 3	Continuous9	30	15
	Alter9	36	9
tester 4	Continuous9	33	12
	Alter9	38	7

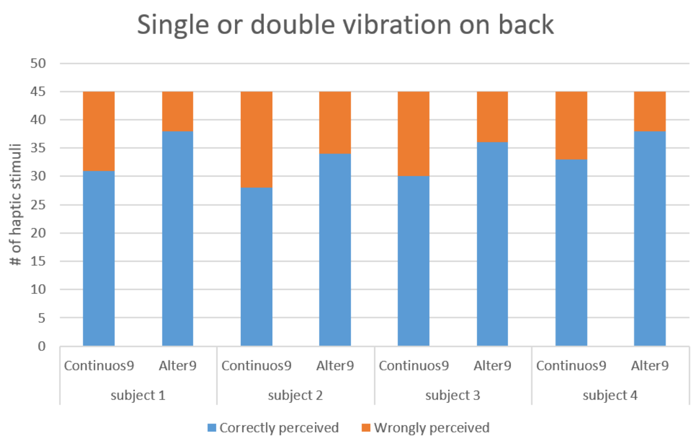


Figure 4.16: Diagram of haptic response of test Continuous9 and Alter9 on back.

In the test Continuous9 we have a right detection rate of 67.8 %. For the test Alter9 we have a right detection rate of 81.1%. From this set of test, we understand that the alternating vibrating rate has a better right perception rate on the wrist. Every participant is able to say properly when all motors are off. Removing from the data set the off condition we have a right detection rate of 63.75 % (Continuous5) and 78.75 % (Alter5); the results can be seen in Graph 4.17.

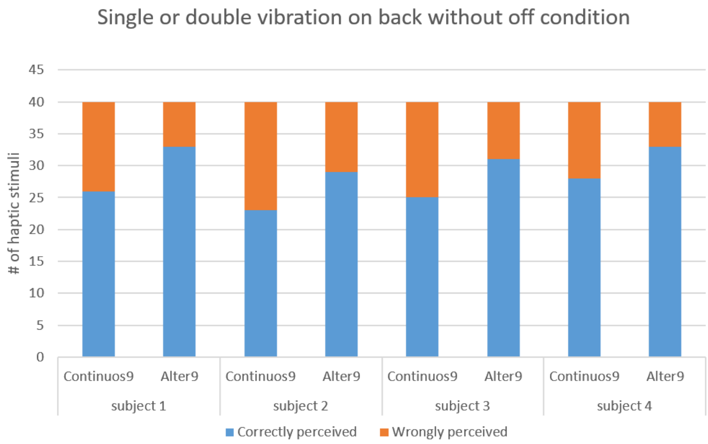


Figure 4.17: Diagram of haptic response of test Continuous9 and Alter9 on back.

In Table 4.10 it is resumed all wrong perceived messages. It is worth notice that all the test subject perceived the position on the ankle as the more uncomfortable. In particular, all the subjects express commented that up and down the spine are easy to be recognized (probably because the dimension of the spine and the sensibility of the spine) but, the left and right are very uncomfortable to recognize. More than 90 % of the time that 2 vibrating motors vibrate at the same time the subjects are able to recognize precisely if is up or down but not if is right or left or even if something other than up or down vibrate.

Table 4.10: Wrong perceived on back

		up	down	right	left	up-right	up-left	down-left	down-right
tester 1	Continuous5	0	0	0	0	x	x	x	x
	Alter5	0	0	0	0	x	x	x	x
	Continuous9	0	0	2	1	3	4	3	2
	Alter9	0	0	1	0	0	3	1	2
tester 2	Continuous5	0	0	1	1	x	x	x	x
	Alter5	0	0	0	1	x	x	x	x
	Continuous9	1	0	3	2	4	3	1	3
	Alter9	0	0	2	1	3	1	2	2
tester 3	Continuous5	0	0	1	2	x	x	x	x
	Alter5	0	0	0	2	x	x	x	x
	Continuous9	0	2	1	0	2	3	4	3
	Alter9	0	1	1	0	1	2	3	1
tester 4	Continuous5	0	1	1	0	x	x	x	x
	Alter5	0	0	1	1	x	x	x	x
	Continuous9	2	0	2	0	1	2	2	3
	Alter9	0	0	1	1	1	2	2	1

4.3.8 Results on total body system

Regarding the tests on the total body, due to the time consumption of this test to the subject, is performed only the Continuous 9 and the Alter9 tests.Different from previous cases now each tester receive 45 messages each for limb (every limb receive 5 messages each for up, down, right, left, off, up-right, up-left, down-right, down-left) for a total of 180 messages for person. The disposition of motors on the body in the distributed configuration on Chapter 3. A maximum of two vibrating motors at the same time vibrate on the body of the testers.

The result of the experiments Continuous9 and Alter9 can be seen in Table 4.11:

Table 4.11: Total body result

		right	wrong
tester 1	Continuous9	107	73
	Alter9	117	63
tester 2	Continuous9	127	53
	Alter9	145	35
tester 3	Continuous9	124	56
	Alter9	146	34
tester 4	Continuous9	139	41
	Alter9	161	19

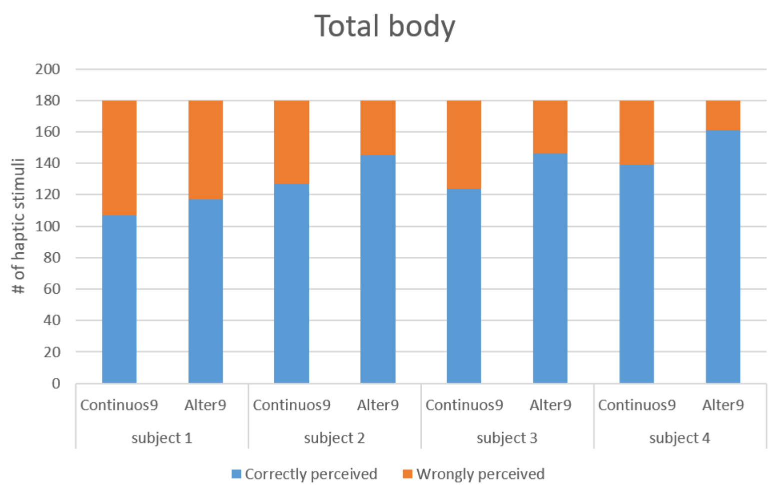


Figure 4.18: Diagram of haptic response of test Continuous9 and Alter9 on total body.

In the test Continuous9 we have a right detection rate of 69.9%. For the test Alter9 we have a right detection rate of 79%. From this set of test, we understand that the alternating vibrating rate has a better right perception rate on the wrist. Every participant is able to say properly when all motors are off. Removing from the data set the off condition, we have a right detection rate of 65.2 % (Continuous9) and 76 % (Alter9); the results can be seen in Graph 4.19.

Table 4.12: Total body without off condition

		right	wrong
tester 1	Continuous9	87	73
	Alter9	97	63
tester 2	Continuous9	107	53
	Alter9	125	35
tester 3	Continuous9	104	56
	Alter9	126	34
tester 4	Continuous9	119	41
	Alter9	141	19

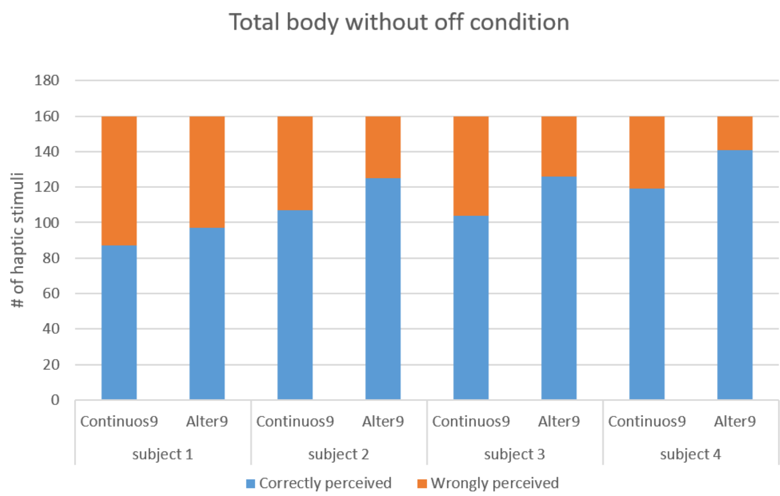


Figure 4.19: Diagram of haptic response of test Continuous9 and Alter9 on total body without off condition.

Chapter 5

Conclusions and future works

The guidance of visual impaired people is a vast and complex topic. One of the most crucial aspect, when guiding blind people, is to choose wisely if it is better to use the auditory or haptic interfaces. The auditory interfaces should be use very sparingly so to not reduce the ability to perceive the external world. With this prospective haptic guidance can be a valuable tool. Another main problem of blind people guidance is that who proposes the solution, most of the time, is not the end user. So in all the implementations we need to involve the user itself. For example, all the tests done in this thesis are done on not visual impaired people but it should be possible that these tests can have different and better results on blinders.

One important concept is that this technology should be considered an additional help in the day to day training of the climbers but it doesn't substitute the role of the guide. The role of the guide is not only to guide, but to study the better route for the particular climber.

The results of the device on the total body test are promising: we should consider that the tester had very small time to understand in which way the haptic guidance points to, while on a climbing wall the climber can stop itself for more time to better understand to which direction move. But this work should be considered a preliminary study: to better understand the haptic guidance of this prototype it should be needed a bigger sample of tester, as much as possible, blind and real climbers in order to obtain a stronger statistical value.

Considering these points, the most important future work is to test the prototype in a real climbing wall by a blind person under the supervision of his guide to better configure the haptic guidance. Another future work is to encapsulate each haptic device in a 3d printed case in order to be easier to wear.

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