Human Guidance: Suggesting Walking Pace Under Workload*

Tommaso Lisini Baldi[1,2], Gianluca Paolocci[1,2], and Domenico Prattichizzo[1,2]

[1] University of Siena, Department of Information Engineering and Mathematics, Via Roma 56, 53100 Siena, Italy.
[2] Istituto Italiano di Tecnologia, Department of Advanced Robotics, Via Morego 30, 16163 Genova, Italy.
{lisini,paolocci,prattichizzo} @diism.unisi.it

Abstract. This paper presents a comparison between two different approaches to control human walking cadence, with the further aim to assess if the users can synchronize to the suggested rhythm with low efforts while performing other tasks. Elastic haptic bands are used to suggest walking-pace during an exercise aimed at reproducing real industrial or human-robot cooperation task. The proposed system consists of two wearable interfaces for providing timing information to the users, and a pressure sensor to estimate the real gait pattern, thus resulting in a combination of walking-state monitoring and vibro-tactile stimuli to regulate the walking pace. Vibrational stimuli with a constant presentation interval are alternately and repeatedly given to the right and left side of the human body, in accordance with the desired walking cadence. We tested two different interface placements: wrists and ankles. The guidance system has been evaluated under mental and manual workload using an additional task: balancing a small sphere in the center of a flat surface. Experimental results revealed that subjects prefer the ankle position for what concerns wearability, comfort and easiness in task execution. Examples of the proposed approach in daily use are training and coaching in sports, rehabilitation, and human-robot cooperation and interaction.

1 Introduction

Nowadays there is growing interest in technologies and methods to assist people during daily activities; despite many attempts, research on navigation aids is still in its infancy. Most of them rely on vision or hearing as primary communication channels, which could be overloaded in many multi-tasking scenarios. We investigated the opportunity of controlling pedestrian cadence at non-attentional level. Related works demonstrated that walkers are able to synchronize to auditory and visual cues [5], but this approach demands more attention and may

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conflict with daily tasks due to the limited resources availability [22]. The interaction with electronics and mechanical devices may arise interference due to the dependency on visual and auditory channels, contributing to overload, thus reduce, sensory perceptions [13,19]. A clear way to reduce cognitive load consists in replacing the audiovisual cues with stimuli involving other senses. This prevents channels from saturating and lowers the overall mental efforts [3].

Our method exploits a feature of the human sensory-motor system, called sensory-motor entrainment, to suggest a specific walking cadence [6,14]. It is known that the frequency of a cyclic movement, such as walking and running, can be affected by rhythmic sensory inputs and can smoothly converge to the input rhythm. For example, when people walk while listening to music, their step cycle gradually conforms to the rhythm of the music. Recent works highlighted how haptic stimuli can be used to deliver walking cadence with minimal interference to other sensory channels, which might lead to better user safety or task execution. In this paper we outline how, given a desired walking pace, users can adjust their gait cadence to match it with little error and minimal effort by means of vibro-tactile cues. The coordination of a team of humans for sport training and the cooperation between humans and robots, represent two examples among the numerous guidance scenarios. Haptic communication offers an effective, yet non-intrusive, way for providing cues to the users when visual modality is temporarily impaired or the audio modality is overloaded by background noise. The underlying idea is that audio or visual systems do not represent the right solutions to guide the walking velocity of a subject while hands are involved in a task, such as assembling parts in an industrial environment or writing on a touch display. By freeing cognitive and attentional resources, the users can carry out their tasks with improved safety and quality.

Recently, several systems based on haptics have been developed, most of which focus on providing stimuli mainly via bracelets and waist belts. More in detail, a torso-mounted vibro-tactile display was used to provide cues for improving situational awareness of soldiers in a simulated building-clearing exercise [10]. In [4] and [20], a vibro-tactile belt was used for human guidance in indoor and outdoor environments, respectively. In [17], the authors used vibro-tactile armbands to guide users along a predefined path, assisted by a mobile robot. In addition, in [3] the authors exploited the use of haptic stimuli for indoors pedestrian guidance using two wrist-worn interfaces. Vibro-tactile armbands were used to navigate subjects along fixed and dynamic paths [2,11], where three basic haptic cues were sent to the user to steer the locomotion. Adame *et al.* in [1] proposed a comparison among different vibro-tactile devices for guidance of visually impaired users. Most of the contributions in literature focused on how to suggest a given rotation to the human body, or how to steer humans along a certain trajectory. An often undervalued important parameter to guide locomotion is the time to reach the target *i.e.*, the steps cadence. Haptic interfaces placed at the subjects feet were used to regulate gait frequency through vibrations in [21]. In [8] the authors presented an interesting vibro-tactile guidance method to suggest cadence to users by means of haptics. An exemplar application is guiding subjects toward the closest bus stop at the optimal walking speed. Also post-stroke rehabilitation benefits from periodic vibro-tactile cues, in terms of increase in subjects' step length and synchronization to the provided rhythm, compared to audio and visual signals [7].

With this work, we present results concerning the idea of using haptic interfaces to suggest walking pace when users are asked to accomplish additional tasks. We tried to replicate the traits of a real scenario, such as human-robot cooperation and industrial tasks. In particular we concentrate on applications where the operator use her/his hands to perform manipulation tasks while walking towards a target.

Two different solutions to provide the periodic vibro-tactile guidance have been tested and compared with the approach proposed in [8], to extend it under cognitive and manual load.

2 Human pace suggestion via haptic feedback

In this Section we analyze the gait synchronization strategy developed to control the user gait cadence. The principles of our guidance approach are based on the step cycle schema proposed by Philippson in [15]. A step consists of a limb movement performed from heel strike to next heel strike of the same foot. The step cycle and length are defined as temporal duration and spatial distance of a single step.

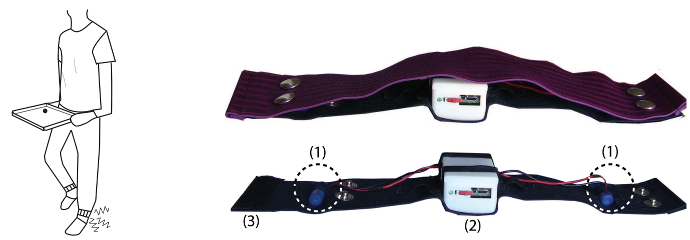
In our method, haptic stimuli, *i.e.*, vibrations, are periodically provided to different left/right body parts to assess which is the most suitable haptic input location. The user mean gait cadence is measured using a pressure sensor placed under the right foot, and is compared with the suggested cadence.

In this paper we want to investigate whether it is more beneficial to place the haptic interface on the wrists or the ankles while humans are performing additional tasks. To identify which is the best location for the haptic stimulation in a work environment, we asked participants to perform additional tasks, which purpose was to increase the manual and mental workload to verify differences in performances related to the haptic bands locations. Synchronization capability and comfort are the metrics used to evaluate the best body location.

2.1 System overview

The proposed system is composed of two parts: the former is in charge of providing haptic cues to the user, whereas the latter, used only for experimental testing and validation, detects contacts between the foot and the ground, thus to compute the user cadence. In what follows we describe the two components of the system.

Haptic bands The desired cadence is suggested to the users through rhythmic vibrations provided by remotely controlled elastic haptic bands. Each wearable



(a) (b)

Fig. 1. Cadence cues are provided to the users via two vibro-tactile elastic bands placed on the wrists or on the ankles (a) of the user during a task with manual and cognitive load. The haptic bands (b) are composed of two vibrating motors (1) attached to an elastic wristband (3). A Li-Ion battery is in charge of power and an Arduino board controls the interface (2).

haptic interface is composed by two water-proof vibro-motors, which can be independently controlled (Fig. 1). Whenever a trigger is sent to a haptic device, the motors vibrate providing a vibro-tactile stimulus to the wearer. In order not to overload the user's tactile channel and reduce the recognition time, we do not modulate the frequency of the signal, but we use a simple on/off mechanism, similar to the one used in [18]. We activate alternatively the two devices in accordance with the desired gait cycle. An additional stimulus to *stop* the user by activating both the haptic devices is implemented. When an interface is activated, its motors vibrate for 0.1s at a frequency of 250Hz. Subjects wear one haptic bracelet on each ankle or wrist in order to maximize the stimuli separation, keeping the discrimination process as intuitive as possible.

The communication is realized with an RN-42 Bluetooth antenna connected to a 3.3V Arduino pro-mini. The wireless connection baud rate is 57600bps. The microcontroller installed on the board is used to independently control the activation of each motor and receiving data from an external PC. Note that the proposed vibro-motors are controlled by applying a certain amount of voltage which determines both frequency and amplitude. Thus, we can not change frequency and amplitude independently. As the user's maximal sensitivity is achieved around 200-300 Hz [16] (the human perceptibility range is between 20Hz and 400Hz), two Precision Microdrives Pico Vibe vibration motors are placed into two fabric pockets inside the bracelet (the width of the wristband is about 60mm), with vertically aligned shafts. The motors have a vibration frequency range of 100-300Hz, lag time of about 20ms, rise and stop time of 35ms. The bracelet guarantees about 4 hours of battery life with one motor always turned on. Each bracelet weights about 90g.

Pressure Sensor The second component has been developed to capture the walking pattern, with the aim to extract the step timing. Its function is the heel strike detection and it is composed by a flexible force sensor (FSR 400,

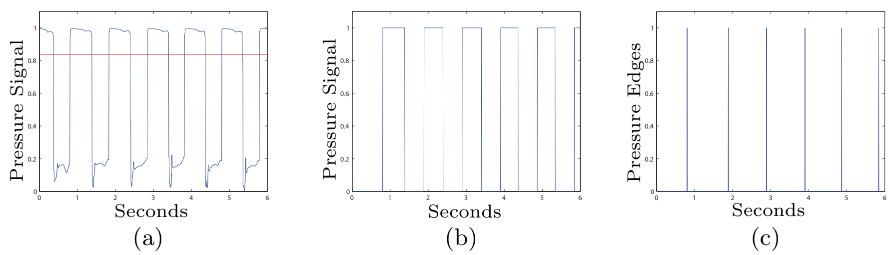


Fig. 2. The pressure values are recorded by a flexible force sensor (FSR 400) and sent wireless through a XBee radio module. The raw signal showed in (a) is normalized between 0 and 1. Steps are extracted by thresholding the raw signal (b), and only considering the positive edges (c). The threshold is set at $2{*}STD$ (Standard Deviation).

manufactured by Interlink Electronics, Inc.) and a XBee radio module. The force sensing resistor measures the force applied through the deformation of the active surface, which produces a resistance variation. We use this component as unobtrusive and comfortable switch to detect the contact of the shoe with the ground. The XBee module is used to convert an analog signal into a digital signal and send it wirelessly to another module, connected to the laptop. The pressure value is converted into a 10 bit digital signal. The step extraction procedure exploits a single-threshold value, defined as the double of the standard deviation of the data, measured during the initialization phase (see Sect. 3). The sensor records the pressure under the heel at 100 Hz. Thus, we are able to measure the step cycle and monitor the walking state from the obtained data. The step-detection procedure consists of three phases. In the first step, raw pressure data are acquired by the system and normalized (Fig. 2(a), then it is transformed into a two-levels signal using a custom threshold (Fig. 2(b)). The square wave indicates whether the foot is in contact or not with the ground, assuming value 1 or 0, respectively. Then, the algorithm extracts positive edges matching the contact of the heel with the floor, identifying the step as the interval between two consecutive edges. Let the number of steps per minute be the *stride-frequency* and the space between two subsequent steps the *stride-length*. *Walking velocity* can be thus computed as the product of *stride-frequency* and *stride-lenght*. Even if the walking speed seems to be controlled by two parameters, Laurent *et al.* in [9] demonstrated that the gait can be controlled acting on only one of the two parameters. We decide to control the stride-frequency.

3 Experimental Validation

We validated the proposed walking-pace suggestion technique using two different body locations for the haptic interfaces, wrist and ankle.

Preliminary test We started the experimental validation of our system by exploiting the results presented in [8]. We performed preliminary tests using haptic interfaces either as bracelets or anklets. Eight healthy subjects walked for 220 m. Three step duration values were tested for each configuration. Each test S_i was labeled according to the suggested walking pace ($i = \{1, 2, 3\}$ corresponding to the desired step cycles of 0.8, 1.0, and 1.2 seconds, respectively). We selected these values to test the system since we observed in preparatory experiments that 0.8 - 1.2 s is a suitable range considering the standard human comfortable cadence. The aim of this test was to verify the attitude of our system in suggesting walking speed and computing a rough estimation of users' response. Users, step duration and body location were pseudo-randomly selected. We discarded the first 4s of data, where the participant is transitioning from stationary to walking state. During task execution, participants wore headphones reproducing white noise to be acoustically insulated from the environment and avoid cues generated from the motors vibrations. The metric is the error in adapting to the proposed rhythm. We defined the error as the average of the difference between subjects' and desired stride duration per each step, normalized and expressed in percentage (with respect to the suggested cadence):

$$error = \frac{1}{N}\sum_{k=1}^{N}\left|\frac{u(k)-d(k)}{d(k)}\right| \times 100\%. \tag{1}$$

Where N is the number of steps walked during the test, u_k and d_k are the duration of the $k-th$ step and the desired time, respectively. The standard deviation of the error, calculated for each subject, is considered the user synchronization capability. In fact, the higher is the standard deviation the bigger is the difference in step duration. In Sect. 4.1 we report and discuss results with statistical tests.

3.1 Cognitive load

The main objective of this work is to compare the performance of the haptic guidance method for users performing tasks requiring cognitive load. In line with the aim of the paper, two conditions were considered: vibrations provided on wrists and ankles.

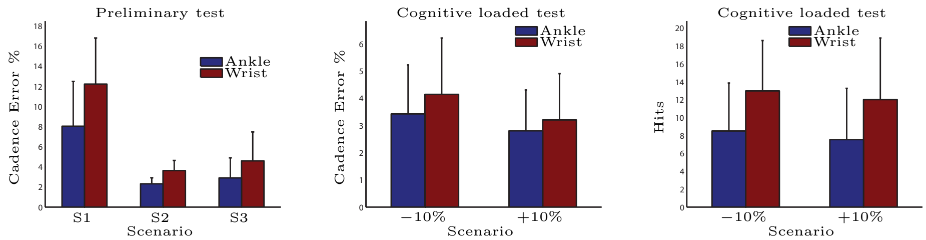
Once the capability of suggesting walking pace using vibrations was established, and a candidate interface location was determined in absence of secondary tasks, we studied the potential of the proposed system in association with manual and cognitive tasks. To increase the subject cognitive load during the synchronized walk a balancing ball-plate game has been designed in a preparatory phase. This task involved the use of both hands, to simulate a real work situation, and required a discrete effort to successfully accomplish the trial.

The aim of the task was to maintain a ball inside a plate avoiding contacts with the edges. It can be considered very close to a real task: maintaining a ball in the center of a plate involves hands, eyes, and it is not excessively immersive. Moreover, we can score and rate how the user is performing the tasks. The plate is equipped with a touch sensor on the border, thus the number of hits (*i.e.* errors in execution) gives a score on the accomplishment.

The evaluation of the system with additional cognitive load was performed on 16 healthy subjects (10 males, age range 23-35): one of them had experience with the proposed vibro-tactile device, the remaining users had less or no experience with our haptic interfaces. None of the participants reported any deficiencies in perception abilities or physical impairments. To enrich the discussion after the trials and to better understand the results, we estimated the user's physiological cadence at the beginning of the experiment. We asked users to walk for the entire pathway without haptic suggestions. In the first 20 meters we checked and calibrated the pressure sensor, whereas in the remaining we evaluate the most comfortable walking cadence while the user acquainted with the pathway. Then, subjects were asked to synchronize the gait cadence to the vibrations provided by the haptic devices. Two values of cadence were tested: $\pm 10\%$ with respect to the comfortable one (previously estimated). We adopted user-dependent cadences to preserve uniformity in testing an heterogeneous set of volunteer with variegated ages, heights, and walking habits. Each participant performed 5 trials: the comfortable gait cycle was estimated during the first trial, then the 4 remaining trials were haptic-guided. Subjects and desired walking pace were sorted in a pseudo-random order. Our setup was not designed to measure the step length, so we refer to the mean cadence, which is the inverse of the mean step duration. During task execution, participants wore headphones reproducing white noise to acoustically insulate them from the environment and avoid cues generated from the motors vibrations. As the primary hypothesis was to provide a purely tactile stimulus, the white noise was designed to cover the motor vibration noise. Each subject was followed by a ghost operator equipped with a laptop for data acquisition, walking at distance of about 5 meters behind. This distance was selected not to disturb the task execution, while keeping the communication active between the wireless devices. Furthermore, vibrations parameters were manually set by the operator via an ad-hoc software. The operator was also in charge of starting the pressure data recording, using the same software. The pressure sensor was placed in the same position of the previous experimental setup. The pressure sensor placement has proven critical for the success of the measurement: the optimal place was the posterior part of the sole, where there was no contact with the foot during the swing phase. We selected this location after numerous prior tests.

4 Results and Discussion

In this section we analyse the data collected in the experimental phase (see Sect. 3) by means of statistical tests to give a more accurate and reliable interpretation, then we proceed with a discussion on the users questionnaire responses.



(a) (b) (c)

Fig. 3. Results of the experimental validation, divided by scenario. Blue bars represent data where haptic cues were provided to the wrist, whereas red bars represent data where information was displayed at ankle location. (a) Preliminary test. In S1 users were asked to follow a 0.8 seconds step cycle, 1.0 and 1.2 seconds were asked in S2 and S3 respectively. (b-c) Cognitive test. Two values of step cycle were tested: $\pm 10\%$ with respect to the comfortable pace. In (b) we report error in maintaining the suggested cadence, whereas in (c) bars depict error in performing the task (*i.e.*, number of hits).

4.1 Results and Statistical Analysis

Preliminary test Regarding the preparatory test, for each user we compared the gait cycle error (mean and standard deviation) in trials with different haptic interface body locations. We calculated the difference between the synchronization error while performing the "ankle" trials and the error in the "wrist" trials of the same subjects, at the same desired cadence, and then we ran statistical analysis on that data. Visual representation is summarized in Fig 3. Experimental results revealed an average error among all trials of $6.62 \pm 2.16\%$ and $4.19 \pm 2.33\%$ in the case of interfaces worn as bracelets and anklets, respectively. Since we were interested in selecting the optimal location, we performed statistical analysis tests to assess if the difference in error was significant or not. Resulting errors were normally distributed, as assessed by Shapiro-Wilk's test ($p = 0.365 > 0.05$). Statistical tests revealed a mean gait cycle error reduction of $2.43 \pm 0.85\%$ while wearing haptic interfaces as anklet with respect to the wrist placement. The paired samples t-test underlined a statistically significant decrement of the mean error using anklets ($t(23) = 2.829$, $p = 0.012 < 0.05$). Then we ran statistics on the subjects error standard deviation. The Shapiro-Wilk's test assessed the normality of the distribution ($p = 0.770 > 0.05$).

Additionally, three paired-samples t-tests were conducted, to check whether in the three different scenarios (S1, S2, and S3) the metric of interest proved more statistically significant in ankle stimulation with respect to the wrist positioning. For each test, we computed the error percent between the real and desired cadence (cfr. EQ. (1)) and then performed statistical analyses to assert differences in performance between the proposed haptic bands locations. We verified the absence of significant outliers, and the possibility to approximate the dependent variable distributions of the two groups (trials with bracelets and anklets) as normal distributions. None of the tests showed outliers, and the assumption of normality was not violated in any test, as assessed by Shapiro-Wilk's test ($p_1 = 0.366$, $p_2 = 0.312$, $p_3 = 0.646$ for the error mean, and $p_1 = 0.807$, $p_2 = 0.532$, $p_3 = 0.288$ for the error standard deviation). Participants were found to align with the desired cadence more often (*i.e.*, the average error is lower) when the elastic haptic bands were positioned on ankles: outcomes of data analysis showed an error percent reduction of $4.09 \pm 1.69\%$, $1.31 \pm 0.41\%$, and $1.70 \pm 0.55\%$ in scenario S1, S2, and S3 ($t_1(7) = 2.418$, $p < 0.05$, $t_2(7) = 3.160$, $p < 0.05$, $t_3(7) = 3.101$, $p < 0.05$). The mean difference in standard deviation indicated that subjects were able to synchronize more consistently using the haptic interfaces as anklets: values obtained were $1.48 \pm 0.33\%$, $0.75 \pm 0.27\%$, and $1.09 \pm 0.35\%$, respectively in scenario S1, S2, and S3 ($t_1(7) = 3.424$, $p < 0.05$, $t_2(7) = 2.706$, $p < 0.05$, $t_3(7) = 3.072$, $p < 0.05$).

Cognitive test For what concerns the test executed with a not-negligible cognitive load task, we evaluated the results through two different metrics: the error in following the suggested step frequency and the number of times the ball hit the tray margin during the task execution. In Fig. 3(b) and Fig. 3(c) we pictorially summarize the experimental evaluation results. On both metrics of interest we carried out statistical tests to validate the results. As we did for the preparatory experiment, we analysed errors on trials with different gait cadence both separately and together. For what concerns all the trial, the wrist location elicited a statistically significant average error increasing of $0.54 \pm 0.17\%$ compared to the ankle. Statistical significance was established using paired-sample t-test ($t(31) = 3.132, p < 0.05$). Values satisfied the Shapiro-Wilk test ensuring a normal distribution of the mean error differences ($p > 0.05$). Additionally, statistical analysis was used to infer about the subjects synchronization. Users maintained a more uniform pace using the the haptic bands as anklets. Difference between error standard deviations using bracelets and anklets resulted to be $0.22 \pm 0.06\%$. The Shapiro-Wilk test verified the distribution normality ($p > 0.05$) and the paired-sample t-test confirmed the statistical significance ($t(31) = 3.768, p < 0.05$). Moreover, we performed single paired-sample t-test for each condition, investigating whether the increasing in performance is related to the position of the haptic bands for each scenario. For both gait cycle conditions we compared the error mean values. The ankle solution, compared to the wrist location, elicited an average error reduction of $0.26 \pm 0.11\%$ ($t(15) = 2.339$, $p < 0.05$) in following the slower rhythm and $0.80 \pm 0.31\%$ ($t(15) = 2.607$, $p < 0.05$) for the faster one. The error standard deviation reduction is $0.20 \pm 0.08\%$ ($t(15) = 2.335$, $p < 0.05$) in following the slower rhythm and $0.25 \pm 0.08\%$ ($t(15) = 2.903$, $p < 0.05$) for the faster one. Error are expressed as percentage of the trial requested cadence.

Data from participants were analysed to understand the correlation of haptic suggestions and task performance. Number of errors (hits against the touch sensor) was used as a metric. Of the 32 trials (2 for each participant to the study), the wrist location elicited an increase in mistakes in 26 trials compared to the ankle position, whereas two trials saw no change. Moreover, results in accomplishing the requested task were analysed to further understand the correlation of haptic suggestions and task performance. Of the 16 participants recruited to the study, the anklet position elicited a reduction in hits in 12 participants compared to the wrist position, whereas one participant saw no improvement and 2 performed better with the bracelets. We performed Wilcoxon signed-rank tests considering both separating trials by gait cycle (+10%, and -10% with respect to the physiological), and together. Trials with higher cadence (-10%) showed a statistically significant median reduction in hits (4 hits) when subjects wore anklets (7 hits) compared to the bracelets (11 hits), $z = 2.051$, $p < 0.05$. Also outputs of the test conducted on the slowed pace (+10%) confirmed an improvement in executing the task with the anklets. The median number of hits wearing haptic interfaces in the ankles drew from 11 to 8, resulting in a median reduction of 3 hits ($z = 3.087$, $p < 0.05$).

Qualitative user feedback In addition to the statistical results, we take into account also the users' point of view. The aim of this paper is to compare different haptic guidance strategies for real applications. Thus, not only numbers but also personal experiences represent a key value. At the end of the trials, a survey based on the Usability and User Experience (USE) [12] in the form of a bipolar Likert-type was proposed to the subjects. The USE questionnaire evaluates three dimensions of usability: comfort, ease of use, and wearability. Each feature is evaluated using a number of items: subjects must select a mark on a seven-point scale (1 = *strongly prefer Wrist*, 7 = *strongly prefer Ankle*). Results are shown in Table 1.

Table 1. Questionnaire factors and relative marks.

Questionnaire factors	**Mean (SD)**
Comfort	6.33 (0.88)
Ease of use	3.82 (0.90)
Wearability	5.67 (1.10)

Marks range from "*1 = strongly prefer Wrist*" to "*7 = strongly prefer Ankle*". Mean and standard deviation (Mean (SD)) are reported.

4.2 Discussion

Based on the results explained and detailed in the previous section, and from Table 1, we can assert that the ankle is the most suitable location for suggesting walking pace under mental and manual load. The test revealed that wearing the haptic interfaces in the ankles slightly increased the capability of guiding the walking pace. Several subjects stated to prefer the ankle position because they had an immediate feedback on the prediction of the next vibration thanks to the contact with the ground at the heel strike. Observing both the result graphs (Fig. 3) and the statistical test outputs, we observed that the farther the required cadence was from the comfortable one (in average 1 second per step cycle), the greater was the difference in performances between the two adopted guiding policies. Moreover, from the outcomes of these trials we noticed that the higher was the required cadence, the higher was the error.

In addition to the improvement of the performance highlighted by statistical analysis, subjects rated positively the ankle version of the system. For what concerns the easy of use, since the working principle is the same for both anklets and bracelets, results outline the equivalence of the two approaches. Without any doubt, we can affirm that the subjects strictly prefer the anklets from the comfort point of view. Users motivated this choice since the vibration in the arm was considered at the same time both a pace suggestion and a disturbance to the task. They were using their hands to balance a ball; a vibrations represented an interference in the task execution. For what concerns the last factor, the wearability feature, the questionnaire results revealed that users prefer the anklets with respect to the bracelets. This answer can be attributed to the subjects often wearing bracelets, watches and other accessories on their forearm. Despite the haptic device being lightweight (89.3 g), subjects preferred wearing it on their legs because it felt less constraining and tiring. A further suggestion users gave us after the experimental session was the possibility to hide more easily the haptic interface under their clothes in the case of anklet.

5 Conclusions

In this paper, we report preliminary results regarding the problem of guiding humans by modifying their step duration *i.e.*, the linear velocity. Haptic stimulation is used as an interesting way to provide velocity information when audio or visual channels are not available or overloaded. We consider two different location for displaying vibrations and suggesting walking pace, the wrist and the ankle. A task requiring a not negligible cognitive load was assigned to users. Experimental evaluation and subjects usage feedback showed a preference for the ankle location. Such body position resulted in a smaller error regarding rhythm synchronization and better performances in executing a real task; it also was preferred by the users for usability, wearability and comfort.

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