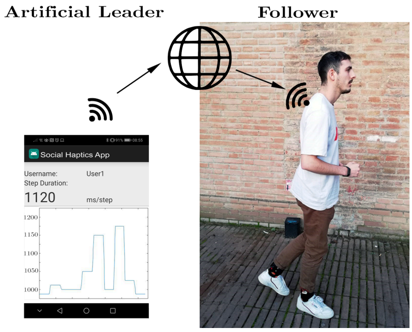
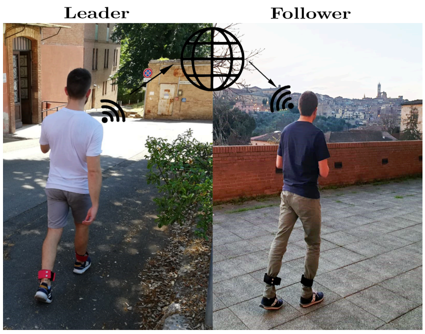
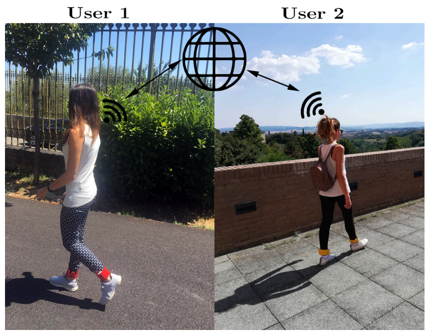


(a)



(b)



(c)

Figure 2.8: In (a) we examined the human capability in entraining to an external rhythm generated by an algorithm. The suggested cadence could be either constant or time-varying (see Artificial Constant Reference and Artificial Leader). In (b) a representative frame of the Human Leader experiment is depicted. The follower is asked to synchronize to the gait pace of another human using the proposed system. This experiment differs from the previous one since the human's stride duration is not regular, but features small unpredictable variations. Finally, in the Peer-to-peer configuration (c) we tested the bidirectional capability of our system. Both participants were sending each other their respective gait cadence (sensed by their anklet devices). The direction of the information is graphically represented by the arrows.

Preparatory experiments

As a preparatory phase, we conducted an experimental campaign to assess whether humans are able to synchronize gait events, *e.g.* the heel strike or lift off, with vibrations displaying a constant rhythm close to the participant's walking cadence. Two hypotheses were formulated and tested: *i*) humans are capable of aligning their stride sequence to an external rhythm displayed using vibrations; *ii*) humans can maintain the suggested walking cadence in presence of a simple secondary task. While the first hypothesis lays the basis for future experiments, the second is tested to understand if it is possible to perform actions which do not require heavy cognitive load while using our system.

Artificial constant reference

As a second phase, we conducted the analysis of human synchronization with an external haptic stimulation by investigating the dependence of human alignment performance from the sign of the cadence variation. In this experiment, participants were tasked to match their stride frequency with paces both slower and faster than the baseline.

Artificial leader

As a further step towards the goal of creating a remote walking system, we had to verify whether humans promptly respond to frequency variations of the haptic cues.

We designed the simplest situation for measuring to which extent a human is capable of adjusting his gait cadence to match a time-varying reference (Fig. 2.8a). Each trial involved only one user who was instructed to follow as close as possible an external rhythm. The stimulus frequency was updated every 30 seconds while remaining in a specific interval. The purpose of this experiment is to determine whether a properly instructed human can adapt with ease to a time-varying cadence. Therefore we measured the discrepancies between the reference and the human cadence.

Human leader

The next step toward the remote social walking was replacing the computer program adopted in the 'Artificial Leader' experiment with an actual human. The purpose of this scientific question was to determine whether a human can follow the gait cadence of another human using the proposed system (Fig. 2.8b). This experiment differs from the previous one since the human walking pace is not as regular as an artificially generated rhythm, and can have small unpredictable variations. It is essential to notice that in this scenario the communication was restricted to one direction only: gait cadence values measured on the leader side were sent over to the follower, while no action was taken upon follower's cadence variations. This asymmetry was designed to nullify any synchronization dynamic.

The human follower was instructed to adapt to the perceived gait cadence, whereas the human leader was allowed to walk at his own pace. The leader received no notification regarding the presence of the follower, thus he/she was fully unaware of whether the follower was feeling his/her steps. We measured discrepancies between leader's and follower's gait cadences to study the time needed for the follower to adjust his/her pace and the stability level he/she was capable of maintaining.

Peer-to-peer

In an in-person social walk, *i.e.* when a group of at least two humans walk together, it is an implicit rule that of adjusting the speed so that the group can clump and stick together. Therefore, in the general case there are no specific roles to be given, such as leader and follower, and each participant would contribute to reach an agreed advancement pace.

This is the scenario in which the full capability of our system emerges: both participants were sending their respective gait cadence (sensed by the anklet devices) to the server which broadcasted them in real time to the partner's smartphone that, in turns, applied the vibration frequency (Fig. 2.8c). It follows that if the two walkers advanced with different cadences they would have both experienced a misalignment between their steps and the anklets vibrations.

The experimental guidelines in this case play a paramount role as the feedback loop is established and several consensus dynamics are possible: the instructions determine which of those effectively takes place. We decided to instruct the participants to pursue two competitive goals simultaneously and with the same priority: try to adapt to the other's gait cadence but also try to maintain a comfortable walking, as close as possible to one's own natural cadence.

The scientific questions relevant to this experiment are more articulated than the previous cases: while it is still worth studying the transient before stabilizing to a common cadence, it is also interesting to determine the absolute and relative discrepancies between the common and personal cadences. Moreover, comparing the common cadence during the synchronization phase with the participants' comfortable cadences is indicative in terms of the consensus dynamics between the participants.

2.2.4 Experimental validation

As previously mentioned in the introduction (Subsect. 2.2.1) we conducted a stepwise validation. In this subsection, we retrace the progression of the experimental process describing experimental protocol, setup, and results per each step.

All the experiments have been held at the open-air athletics track in Siena. Participants were provided with written informed consent and suggested to wear sport equipment. The experimental campaign was held in 5 non-consecutive days, one per experiment, and subjects could discontinue participation at any time. Some participants took part in multiple experimental sessions. All were healthy and none had neuromuscolar disorders or recent injuries at the time of study. It is important to point out that in all the trials involving two participants, they were instructed to walk along different paths, avoiding any visual and audio interaction. The only way of communicating was through haptic stimuli.

Preparatory experiments

In this experiment we evaluated the human capability in adapting the gait cadence to an external constant rhythm. Moreover, we tested whether the addition of a secondary task did affect the cadence synchronization performance.

The representative sample consisted of twenty subjects (age 31.7 ± 10.6) with these characteristics: 10 females and 10 males; 6 had previous experiences with haptic interfaces; 2 played music instruments at high level (drums and piano); 12 played sport, two of them in a professional league with regular training sessions.

Participants were provided with an Android phone and two haptic interfaces. The pressure sensor, connected to the master anklet, was positioned under the right heel to sample pressure data and extract stride durations, which were then transmitted via Bluetooth to the smart-phone and logged by the server. In all the trials, participants walked while wearing headphones reproducing white noise to avoid entrainment due to the sound of vibrations and external stimuli.

The first experiment was performed to test the first hypothesis: *"can humans synchronize their gait cadence with the rhythm suggested by the anklets?"* For each participant the experimental session started with a preliminary acquisition of self-paced gait along a 200 m path, to record the user's comfortable cadence. In the second trial the haptic interfaces were activated at a frequency 10% faster than the previously estimated baseline stride duration. Subjects were instructed to align their step sequence to the vibrations during the 200 m walk.

The second hypothesis was tested by adding a secondary task to the experimental protocol described in the first experiment. The purpose of the secondary task was to determine whether the presence of additional mental efforts affected the users' ability to follow the rhythm dictated by the haptics. The secondary task was selected according to the requirement of low mental efforts, described in [93]. Subjects were asked to answer simple mathematical questions (double-digit sums and differences) on a smart-phone app and to walk at the same time, giving the same priority to the two tasks.[1] We adopted the same procedure of

[1] The secondary task proposed in this project is different from the one considered in Subsect. 2.1.3. In that case, the users were asked to iteratively subtract 7 starting from 999, and write all the operations on a text-edit app for smartphone. The task proposed in this work instead requires the user to make simple arithmetic calculations and write the answer only.

the previous experiment: the first trial was meant to estimate the participants' baseline cadence, whereas the second trial was conducted with haptic stimulation enabled and the secondary task. Walking distance was 200 m in both cases and gait parameters investigated in the data analysis were the same as previous experiment.

Results The analysis of comfortable cadence trials yielded baseline information about the gait parameters of our sample. In average, participants' stride duration was 1138 $\pm$ 36 ms, corresponding to a cadence of 52.72 ($\pm$ 2.19) strides/min. The inter-subject cadence variability, expressed in percentage, represents the 4.2% of the average value. This result is in line with the results of [96]. In that work, accelerometer signals recorded during the comfortable cadence walking of 60 subjects were analyzed. The authors reported a mean walking cadence of 53.54 ($\pm$3.87) strides/min, which corresponds to an average stride duration of 1120 $\pm$64 ms. The inter-subject cadence variability was 7.2%. Anyway, those data were recorded while walking on regular and irregular surface, which would motivate the higher variability. We then calculated separately the stride duration variability (standard deviation) for each user, which mean value was 1.93%, to assess the degree of physiological variability of human walking pace.

In order to discriminate changes in walking parameters due to haptic stimulation, we defined three tolerance bands (2%, 4%, and 6%, corresponding to σ, 2σ and 3σ) around the reference stride duration subjects were asked to keep. In fact, we hypothesize that cadence variations in the interval 'stride duration $\pm$6%' (where $\pm$6% represents $\pm 3\sigma$) should be related to physiological variability, and higher misalignment may be due to the user being unable to follow the haptic rhythm. The tolerance bands were then used to investigate the amount of time, expressed in percentage of the trial duration since the beginning the synchronization with the haptic stimulation, in which subjects were able to follow the external pace given the acceptable error. This quantity is referred to as "alignment percentage".

In Table 2.2 we report the synchronization rate for each subject, calculated in the three tolerance bands. The median synchronization rates in the first experiment were 78.84%, 99.28%, and 100.00% for the 2%, 4% and 6% tolerances, respectively. The introduction of the secondary task lowered the overall synchronization rate: 47.50%, 85.92%, and 99.80% were the median values extracted. We assessed through the Shapiro-Wilk's test that the data were not normally distributed, so we visually depicted data by means of box-plots in Fig. 2.9, and numerically using quartiles (reported in Table 2.2).

To assess if the effect of vibrations was relevant, we compared data obtained during comfortable gait and haptic stimulation trials. A paired-samples t-test revealed a statistically significant mean difference in the stride durations recorded

Name	Haptics			Haptics + Secondary Task			Note
	2%	4%	6%	2%	4%	6%	
User1	66,32	99,05	100,00	47,36	84,88	92,59	
User2	89,06	100,00	100,00	88,19	100,00	100,00	★
User3	78,90	98,00	99,80	28,85	78,19	99,60	
User4	47,35	98,83	100,00	78,66	100,00	100,00	
User5	91,13	100,00	100,00	38,88	77,34	87,43	
User6	81,52	96,53	100,00	55,82	93,43	100,00	
User7	89,95	99,69	100,00	36,91	86,95	100,00	
User8	94,78	100,00	100,00	25,19	78,78	100,00	
User9	76,98	98,47	99,96	44,80	80,38	92,29	
User10	80,38	100,00	100,00	67,61	100,00	100,00	★
User11	66,58	94,41	100,00	0,00	4,20	39,82	
User12	41,50	94,30	99,52	34,45	98,54	100,00	
User13	83,28	100,00	100,00	48,96	97,32	100,00	
User14	78,77	94,68	100,00	19,07	62,93	97,33	
User15	76,01	99,50	100,00	76,01	99,52	100,00	
User16	90,76	100,00	100,00	47,63	84,67	94,27	
User17	77,10	98,56	100,00	49,64	81,36	93,68	
User18	88,35	99,60	100,00	50,88	92,36	100,00	
User19	73,78	88,66	99,09	53,58	88,04	91,48	
User20	72,27	100,00	100,00	39,28	82,75	95,68	
Percentile 25	**72.65**	**96.90**	**100.00**	**35.07**	**79.18**	**92.86**	
Percentile 50	**78.84**	**99.28**	**100.00**	**47.50**	**85.92**	**99.80**	
Percentile 75	**88.88**	**100.00**	**100.00**	**55.26**	**98.24**	**100.00**	

Table 2.2: Preliminary Experiment. For each user are reported the percentages of trial duration during which the participant aligned the walking cadence with the reference rhythm, grouped wrt the considered error bands. Please notice that users tagged with ★ are the two high level music players.

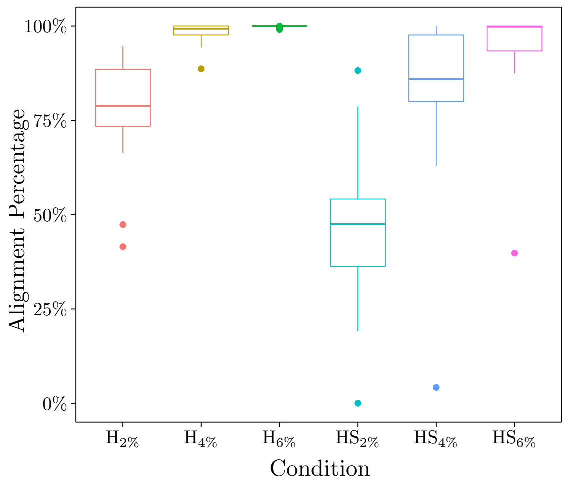


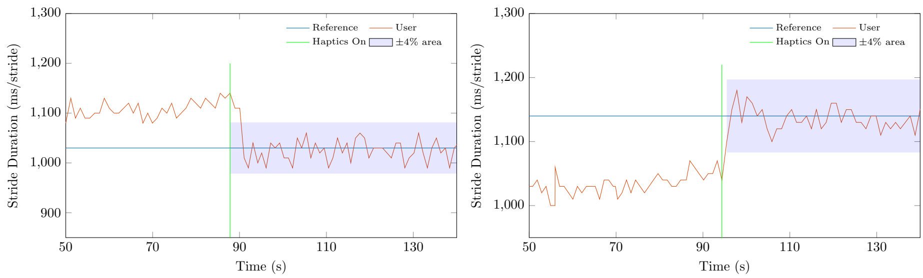
Figure 2.9: Preliminary Experiment. Boxplots represent the distributions of alignment percentages for each condition. Labels **H** and **HS** refer to data acquired during trials with haptic stimulation and haptic stimulation and secondary task, respectively. The subscripts indicate the tolerance band used to discriminate aligned strides from misaligned. The percentage is referred to each subject's baseline stride duration.

in the two conditions ($p = 0.015$). No outlier was detected. For both conditions, the assumption of normality was not violated, as assessed by Shapiro-Wilk's test ($p = 0.195$).

The same procedure was applied for the analysis of gait data recorded during the second experiment. Shapiro-Wilk's test confirmed the normal distribution of mean differences in stride duration per each subjects ($p = 0.583$), and the paired-sample t-test assessed that participants modified their stride duration also in presence of additional cognitive load ($p = 0.04$).

Discussion Experimental results confirmed that humans can synchronize their step sequence to an external, constant rhythm provided through vibrotactile cues, with an error comparable to the natural cadence variability. Thus we can assume that it is possible to influence the participants' average cadence by asking them to voluntarily align to the provided rhythm.

The increase of cognitive load due to the secondary task did not have a relevant



(a)

Figure 2.10: Artificial Constant Reference. Representative epochs for faster and slower cadence suggestion. In (a) the provided haptic rhythm has shorter period than the participant's baseline walking pace, and the user has to walk faster to match the external frequency. The green line represents the instant in which the haptic stimulation is activated, while the blue band highlights the tolerance band used to assess the alignment. Figure (b) is the symmetrical condition for slower cadence (in fact the stride duration reference increases wrt the baseline).

effect on the synchronization, which was achieved for most of the time by all the users, although the variability increased. Only one user could not successfully adapt to the suggested rhythm.

This experiment paved the way and defined some evaluation criteria for the other trials. To the best of our knowledge, literature lacks a clear and unanimous way of evaluating the human cadence synchronization with an external stimulus, therefore a straightforward choice was to use results of this experiment as a metric. The users' average stride duration variability during comfortable walking, in a regular surface without disturbance, is about 2%. Thus, fluctuation around the mean value in the interval of $\pm 4\%$ (2σ) could be considered an appropriate interval for including the majority of the strides walked in a correct tempo. In the following experiments, 4% was used as reference to discriminate strides aligned and non aligned with the reference stride duration.

Artificial constant reference

Since the preparatory experiment only investigated the faster cadence condition, we enrolled 10 new participants (age 28.3 ± 4.3, 7 males) to collect data on symmetrical pace variation. We replicated the setup of the previous case: participants were provided with the hardware, then their baseline cadence was acquired in a 100 m self-paced walk. Each subject was asked to perform two trials, during which they had to voluntarily synchronize their strides to a reference rhythm,

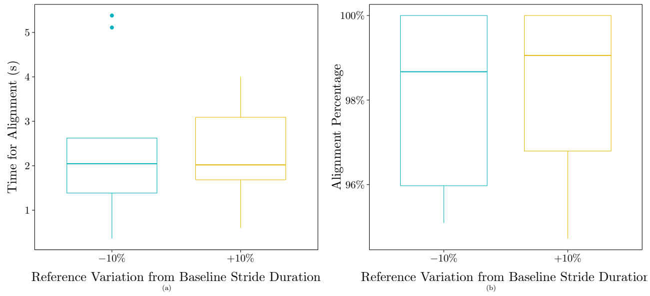


Figure 2.11: Artificial Constant Reference. The left boxplot (a) represents the distribution of times required by participants to align to the suggested pace, for 10% faster and slower cadence wrt to the baseline, respectively. The right boxplot (b) reports the distribution of trial time percentage (after the synchronization) during which participants' stride duration differed less than 4% from the suggested pace. In both cases, performance data show no significant difference due to increasing or decreasing stride duration.

10% slower and faster than the baseline (the order was randomized). Trials were divided in 100 m of self-pace walking and 200 m of haptic-assisted walking. Stride times measured by the master anklet were logged by the system, and then compared with the reference to extract time to reach synchronization and alignment percentage (cfr. Fig. 2.10). In this experimental campaign we did not take into consideration the disturbance due to the secondary task, since we were interested only in the effects of the slower and faster external cadence.

Results Stride duration data were processed to evaluate the time necessary to achieve synchronization with the haptic stimuli frequency, and to determine the deviation from the reference after the initial synchronization. The latter parameter was represented as the percentage of trial time during which the user's cadence drifted from the suggested cadence less than 4%. Shapiro-Wilk's test assessed that the distribution of times required by subjects to synchronize with the external cadence was normally distributed both for the fast ($p = 0.09$) and slow cadence ($p = 0.78$) conditions, while alignment percentages were not normally distributed in both cases ($p = 0.01$ for fast cadence, $p = 0.01$ for slow cadence). Mean time required to match the external stride duration were $2.44 \pm 1.63s$ for fast condition and $2.31 \pm 1.05s$ for slow condition, while median alignment percentages were 98.8% and 99.0% respectively. Boxplots in Fig. 2.11 visually describe data, that are also listed in Table 2.3. Paired t-test conducted on time to alignment val-

User	Baseline Stride Dur. (ms/stride)	Time for Alignment (-10%) (s)	Alignment Percentage (-10%) %	Time for Alignment (+10%) (s)	Alignment Percentage (+10%) %
U1	995	0.4	100.00	3.5	98.11
U2	1146	1.3	100.00	1.5	100.00
U3	1060	1.5	95.23	4.0	94.72
U4	1021	2.6	95.09	3.1	100.00
U5	1078	2.4	100.00	3.1	100.00
U6	975	1.4	100.00	2.1	97.32
U7	1107	2.6	97.34	1.8	100.00
U8	1098	5.4	100.00	0.6	95.21
U9	1100	1.7	97.66	1.9	100.00
U10	1208	5.1	96.38	1.6	98.01

Table 2.3: Artificial Constant Reference. Summary of experimental data. The baseline stride duration represents the average cadence measured during the haptic-off trials. Time for alignment and Alignment percentages are then reported for fast (-10%) and slow cadence condition ($+10\%$).

ues revealed no statistical difference between the two distributions ($t(9) = 0.14$, $p = 0.89$). No statistical test was conducted on alignment percentages because visual representation showed very small difference between the two distributions.

Discussions This experiment was aimed to assess performance asymmetries during faster and slower pace conditions. Experimental results suggest that participants managed to tune their walking pace to the external rhythm for a large portion of the trial duration, regardless of the sign of the cadence variation. The statistical analysis of time to reach synchronization also did not evidence significant differences between conditions. For these reasons, we expect that participants abilities in synchronizing is not asymmetrically biased by the sign of the cadence variation. Forthcoming experimental procedures investigate in detail human acceptance of fast varying gait rhythms, thus broadening the study on the participants' proficiency in aligning to faster and slower paces.

Artificial leader

In this experiment we examined the human capability in entraining to a time-varying rhythm generated by an algorithm. This is a common *modus operandi* in training and rehabilitation bouts, sportspeople and patients have to follow an external pace with time-varying frequency in order to improve (or recover) physical abilities. We named this methodology leader-follower, borrowing the idea from robotics, because the follower is asked to align his step sequence to the haptic rhythm displaying the leader's walking cadence (in this case simulated). Twenty participants (age 29.8 ± 5.3, 14 males) have been recruited for this phase. The experimental setup was composed by two anklets, one of which equipped with the force sensor for recording the stride sequence, headphones reproducing white noise, and a smart-phone with the *ad-hoc* application. Each subject performed a single trial composed of three phases. In the first phase the participant was instructed to walk at his/her comfortable pace for 200 m, to record baseline cadence. In the second phase the user was asked to align to the pace provided through haptic stimuli, for 400 m. In the last phase, vibrations were turned off and the subject continued walking for 200 m at his comfortable pace. A dedicated piece of software simulated the leader's cadence updates that, through the server, instructed the app to vary the vibration frequency. A new reference stride duration was randomly selected every 30 seconds in the interval 900-1100 ms (average stride duration is 1 s). We selected a 30 s update time to analyze the stability of gait cadence after each variation and the number of strides necessary to adapt to the new stride frequency. The second phase of the experiment in average lasted 4 minutes, resulting in at least 7 cadence variations. A representative trial is reported in Fig. 2.12. From each trial we examined: *i)* follower's comfortable cadence before haptic stimulation, *ii)* strides needed by the follower to align his gait with the proposed cadence (considering a 4% tolerance), *iii)* percentage of time the follower is aligned with the suggested gait.

Results The primary aim of this experiment was assessing whether humans could align their cadence to a time-varying frequency. We calculated for each subject the percentage of time in which stride duration was in the range 'reference stride duration ±4%' during the phase with haptic cues. All followers were able to align to the leaders' rhythm for more than 94% of the trial time. Data of the trials are reported in Table 2.4.

The average number of strides necessary to adapt to the new cadence is 2.2 ± 1.2. In particular, an asymmetry was observed between increasing and decreasing stride duration: the number of strides necessary to achieve a misalignment lesser than 4% was 1.1 ± 0.7 and 3.1 ± 1.9 strides for slower and higher frequency variations, respectively. For variations of the reference stride duration below 4% in most cases there was no transient in aligning to the new cadence.

Discussion Outcomes of the test revealed that participants could easily adapt to cadence variations, especially if the difference was small. In fact, considering the human temporal resolution and physiologic variability of gait, the user may not even notice small variations (in the order of 20 ms). These results allow to

User	**Baseline Stride Duration (ms/stride)**	**Time for Alignment (s)**	**Alignment Percentage %**
U1	1206	4.0	100%
U2	1336	4.7	100%
U3	955	3.6	99%
U4	998	1.0	97%
U5	905	3.8	99%
U6	920	0.3	98%
U7	879	4.8	99%
U8	1006	2.9	98%
U9	1060	4.2	95%
U10	986	5.6	100%
U11	881	4.5	99%
U12	885	4.5	99%
U13	980	1.5	99%
U14	1009	4.3	98%
U15	1168	1.5	94%
U16	1077	5.5	99%
U17	961	2.1	98%
U18	1058	2.5	100%
U19	1297	2.7	99%
U20	1251	5.4	99%

Table 2.4: Artificial Leader. For each user we report data from the experimental validation: user's comfortable stride duration (*i.e.*, without haptic suggestion), total time needed to align the actual cadence to the displayed one, percentage of time in which the subject was aligned with the suggested rhythm.

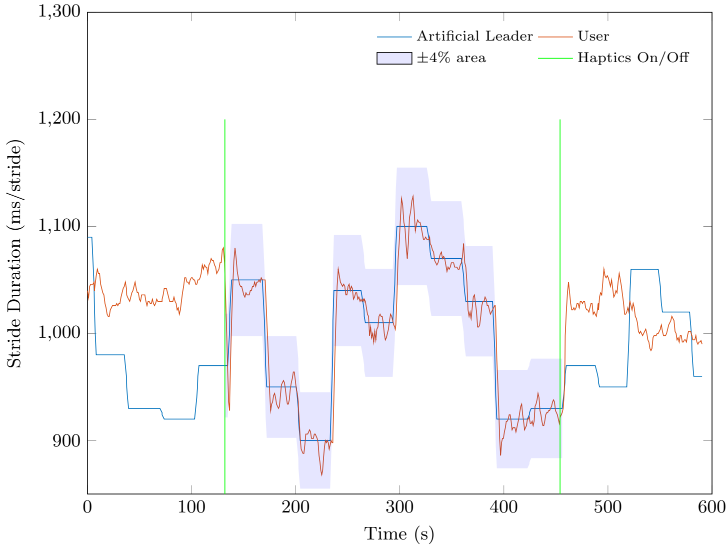


Figure 2.12: Artificial Leader representative trial. The participant was tasked to align his cadence with the one suggested by the wearable haptic devices. The user started the trial walking at his comfortable cadence. After 200 meters the haptics were activated and the user was able to feel the vibrotactile stimulation. The stimulation continued for 400 meters, than the interfaces were turned off. The participant walked for additional 200 meters at his most comfortable cadence. Green lines identify the time-points in which haptics were turned on and off. The user's stride duration is depicted with a red line, whereas the blue line and the surrounding violet area represent the suggested rhythm and the ±4% interval, respectively.

study the synchronization of human cadence with external rhythms which vary continuously, but with limited oscillations, as in the case of human gait. For variations greater than 4%, results show that users react quickly to cadence increase (*i.e.*, smaller stride duration), probably by making smaller steps to restore the synchronization with the external rhythm, whereas it seems more difficult to rapidly reduce the pace (*i.e.*, increase the stride duration). The last phase of recording without haptics is not studied quantitatively; we plot it to demonstrate the effect of the haptic stimulation. In fact, after the vibrations were turned off, the self-selected stride duration was restored to the baseline value.

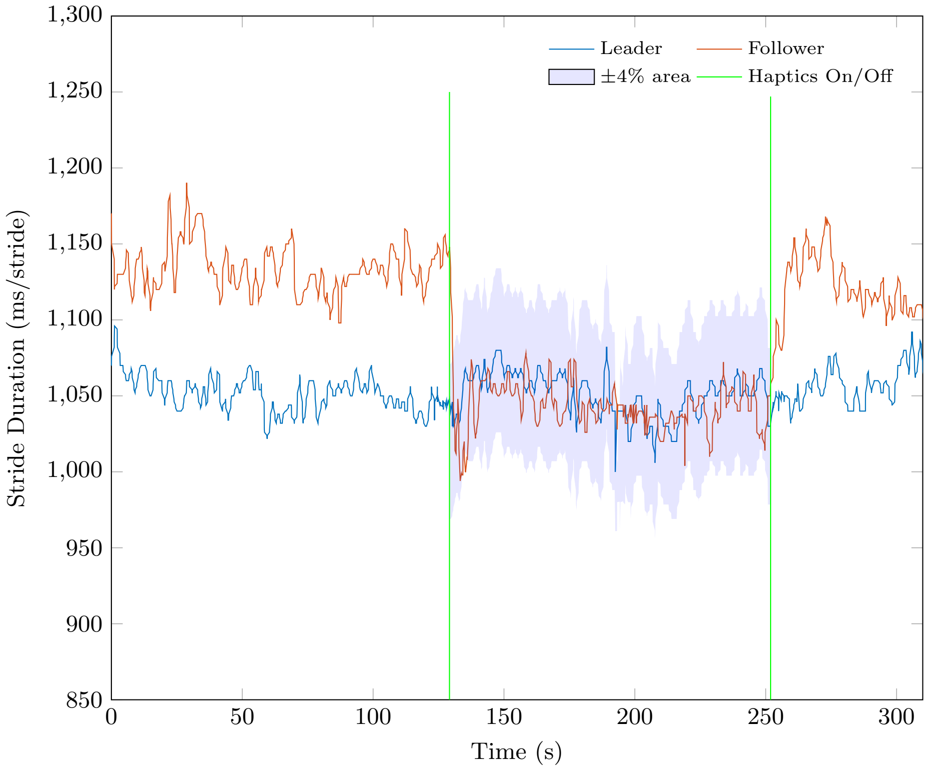


Figure 2.13: Human Leader representative trial. The follower was tasked to align the walking cadence with the leader's one, displayed by the wearable haptic devices. The users started the trial walking at their comfortable pace. After 200 meters, the follower's haptic interfaces were activated, while the leader continued walking at self-selected pace. After 200 meters, the follower's anklets were turned off and the participants walked for additional 200 meters without haptic suggestions. Green lines identify the instants in which the follower's haptic intefaces were turned on and off. The follower's stride duration is depicted with a red line, whereas the blue line and the surrounding violet area represent the leader's rhythm and the ±4% area, respectively.

Human leader

The results obtained in the previous experiment encouraged the assumption that humans can adapt with ease their walking cadence to time-varying rhythms if

Leader	Follower	Leader B Stride Duration (ms/stride)	Follower B Stride Duration (ms/stride)	Mean H Stride Duration (ms/stride)	STD H Stride Duration (ms/stride)	Time for Alignment (s)	Alignment Percentage %
U1	U2	1023	1141	1022	19	2.0	97%
U3	U4	1145	1035	1151	21	4.4	99%
U5	U6	1025	1136	1037	17	3.5	94%
U7	U8	1014	1081	1017	16	3.2	98%
U9	U10	1050	1082	1042	18	3.9	96%
U11	U12	1113	1106	1110	17	3.2	99%
U13	U14	1020	1070	1024	16	2.5	95%
U15	U16	1086	1030	1078	20	3.9	98%
U17	U18	1055	1101	1059	23	3.0	94%
U19	U20	1018	1081	1030	20	3.5	98%
AVERAGE					**18.7**	**3.31**	**96.8%**

Table 2.5: Human Leader. The table reports data regarding the experiment with the human leader, where **B** and **H** stand for baseline and haptic-on condition, respectively. Mean stride durations estimated in the first part of the trial (without haptics) are reported for both the users, and compared to the average walking rhythm during the phase with the haptic stimulation (Mean H). Mean and stardard deviation of the stride duration for the H condition only refer to the follower's walking pace, since he/she was the only one influenced by the haptic stimulation.

the variability is limited (assuming the human cadence physiological variability as boundaries). In this experimental session the follower is provided with haptic stimuli replicating the human leader's cadence. We stress that in this experiment the leader could not feel the follower's steps by any means.

Twenty subjects (age 27.9 ± 6.1, 12 males) took part in this phase. The experimental setup for each participant was composed by two haptic interfaces, one of which equipped with the force sensor for recording the stride sequence, headphones reproducing white noise, a smart-phone with the *ad-hoc* app. The 20 participants, randomly labeled from U1 to U20, were arranged in couples. Each couple performed one trial, the role of leader and follower was selected randomly at the beginning of the trial. In the first phase of the trial, both participants were asked to walk at their comfortable cadence for 200 m, to record gate parameters in the baseline condition. In the second phase the follower received haptic stimuli replicating the leader's gate cadence, to which he had been instructed to adapt. The leader was not notified about the beginning of the second phase, and continued walking at his own pace. The anklets were used by the leader exclusively to record the strides duration, while vibro-motors never activated. After 200 m, haptics were turned off and the last phase began, during which subjects were instructed to walk for 200 m at their comfortable cadence. A representative trial is reported in Fig. 2.13.

From each trial we estimated: *i*) comfortable cadences before haptic stimulation, *ii*) time needed by the follower to align to the leader's cadence (calculated from the initial activation of the haptic devices to the reaching of the desired cadence, considering the 4% error bound), *iii*) percentage of time follower is following the leader's tempo (defined as the follower's cadence ± 4%).

Results Experimental results (detailed in Table 2.5) show that all the followers succeeded in aligning their walking cadence to the leader's one for more than 90% of the time, assuming an acceptable oscillation of 4% around the reference pace. The average time required to align with the leader was 3.31 ± 0.69 seconds.

Discussion In this experimental session we evaluated the human capability in adapting the walking cadence to a fast-varying pace displayed through vibrations. Experimental results show that cadence oscillations due to natural variability do not impede the entraining with haptic cues.

These results open a wide range of applications in which a leader guides one or more followers, as in training and rehabilitation. A more comprehensive discussion on possible future research directions is reported in 2.2.7. Moreover, these results provide the last prerequisites for hypothesizing and testing the mutual cadence alignment, *i.e.* remote social walking, referred in the following as 'peer-to-peer'.

Peer-to-peer

This experimental session represents the last piece of the remote social walking step-wise validation. Once the capability in following an external rhythm was assessed, we tested bilateral transmission of cadence through vibrotactile interfaces to connect two people walking far from each other. Our aim is testing if the system we developed can be successfully used to achieve the cadence synchronization between two users without direct interaction. An assumption we had to make was asking participants to voluntarily align to the partner's cadence, but still keeping a step frequency close to their comfortable one. In fact, the group walking (or social walking) condition is replicated if the participants agree on a common pace comfortable for everyone. As a consequence, in this experiment the users did not receive strict guidelines, they had to 'negotiate' with the partner. Although the psychological aspect plays a relevant role in the achievement of the consensus, it will be studied in a future work. In fact, before studying how

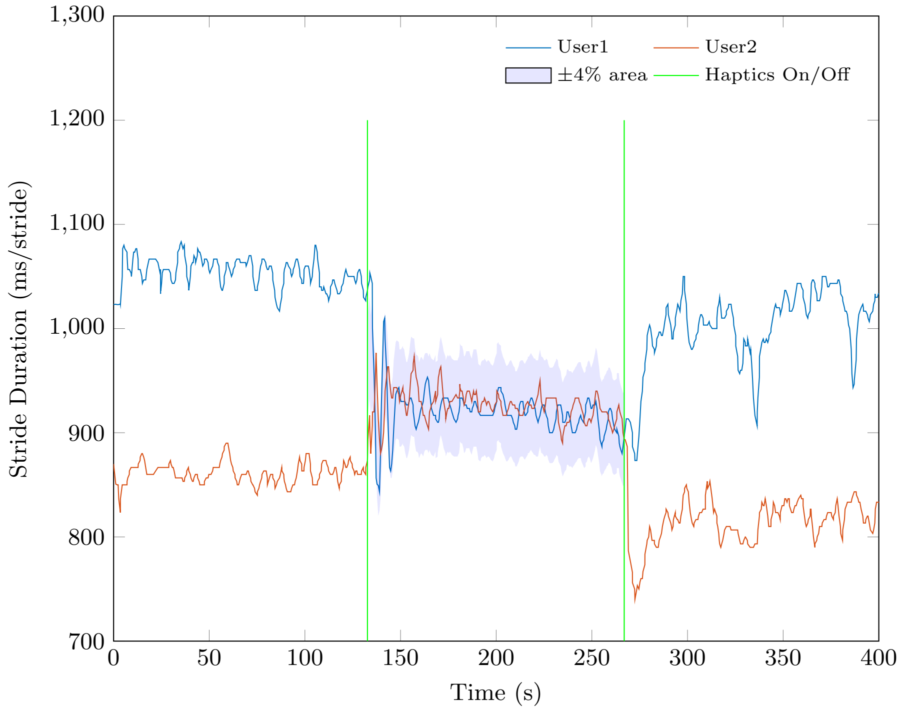


Figure 2.14: Peer-to-peer representative trial. The participants were tasked to align their own gait cadence with the partner's rhythm, displayed by the anklets. The users started the trial walking at their comfortable cadence. After 200 meters the haptics were activated and both users were able to feel the partner's walking tempo for 200 meters. Then the interfaces were turned off again and the participants walked for additional 200 meters at their comfortable cadence. Green lines identify the time-points in which haptic interfaces were turned on and off. The users' stride durations are depicted respectively with red and blue lines; the surrounding violet area represents the ±4% variation with respect to the average stride duration of the two users computed at each timestamp.

people agree on a common rhythm, we need to validate the proposed system and assess if and how the cadence alignment takes place. Thus, in this work we study temporal gait parameters to investigate the system features and capabilities.

Twenty participants were enrolled for the experimental session (age 28.1±5.4, 8 males), randomly labeled from U1 to U20, and arranged in couples. All the users took part in a previous experiment, at least. The experimental setup for

User1	User2	User1 B Stride Duration (ms/stride)	User2 B Stride Duration (ms/stride)	Mean H Stride Duration (ms/stride)	STD H Stride Duration (ms/stride)	Time for Alignment (s)	Alignment percentage %	User1 Variation %	User2 Variation %
U1	U2	1082	1158	1136	18	3.6	95%	5%	2%
U3	U4	1060	1002	1023	25	5.2	96%	4%	2%
U5	U6	1139	1136	1190	32	4.2	96%	4%	5%
U7	U8	1004	1070	1083	25	2.8	91%	7%	1%
U9	U10	1039	982	1046	31	1.1	92%	1%	6%
U11	U12	1067	1047	1090	35	5.6	93%	2%	4%
U13	U14	996	1167	1087	33	11.6	99%	8%	7%
U15	U16	1102	1119	1145	33	7.3	86%	4%	2%
U17	U18	1032	1103	1067	22	4.9	99%	3%	3%
U19	U20	1082	1197	1116	24	2.9	98%	3%	7%
AVERAGE					**28**	**4.9**	**94.5%**	**4.1%**	**3.9%**

Table 2.6: Peer-to-peer. The table details data regarding the final experiment. **B** and **H** refer to baseline and haptic-on conditions, respectively. Mean stride durations estimated in the first part of the trial (without haptics) are reported for both the users, and compared to the average walking rhythm during the phase with the haptic stimulation (Mean H).

each subject was composed by two haptic interfaces, one of which equipped with the force sensor for recording the stride sequence, headphones reproducing white noise, a smart-phone with the *ad-hoc* app.

Trials were composed by three phases: users were asked to start from predefined positions and walk at their comfortable pace along different paths for 200 m. In the second phase haptic stimuli representing the partner's cadence were delivered to each participant, who was instructed to adapt to the received rhythm and, simultaneously, try to pull the partner toward his own pace. After both participants walked 200 m, the haptic stimulation was turned off and the users walked at their own cadence for 200 meters. A representative trial is reported in Fig. 2.14.

In order to give a quantitative evaluation of the effectiveness of our system, we introduce the concept of *cadence alignment*: a user's stride is aligned with the partner's if the duration of the current stride is in the interval 'partner's last stride duration $\pm 4\%$'. In this last experiment we analyzed: *i*) comfortable cadences, *ii*) variation of the average cadence for each user during the haptic stimulation phase (with respect to the comfortable cadence), *iii*) time needed for reaching the alignment, *iv*) percentage of time users' strides were aligned.

Results All users, with exception of two, varied their average walking cadence during the phase with haptic stimulation, as visible in Table 2.6. The average stride duration variation with respect to the comfortable pace was 4.0%. In all but two cases the participants agreed on a common cadence which was intermediate between the two comfortable cadences. The average time to reach the cadence alignment was 4.92 ± 2.91 seconds. After the beginning of the alignment, on average, the participants maintained a similar gait frequency (in the limits of 4%) for the $94.5 \pm 4.1\%$ of the time.

Discussion As shown in Table 2.6, all the participants changed their walking pace according to the partners' stride duration after the stimulation was activated, and retrieved their their comfortable cadence after the haptic-enabled phase. It is worth pointing out that the time for aligning the cadence to the partner's is higher than the ones observed in the Leader-Follower case. This is probably a consequence of the fact that both the users try to follow the partner's cadence, resulting in a transient during which the users' stride durations oscillate. In addition, for the majority of the trial, we observed a greater oscillation at the beginning of the haptic cueing, followed by a constant reduction. This is characteristic for a system with an inertia following a reference. Although the study of psychological aspects is not in the focus of this work, we can make two considerations:

i) in most of the trials, the participants aligned their gait cadence on a common rhythm which was close to the mean value of the comfortable cadence of the two users;

ii) in two trials, participants achieved the consensus, but they aligned on a cadence which was close to the comfortable cadence of one of the participants.

2.2.5 Correlation analysis

The presented experimental validation and the following results discussion can be enriched by analyzing the correlation between the participants' self-pace at baseline and their ability to align the walking cadence to the reference pace. In particular, we searched for possible relationships between subjects comfortable cadence, suggested rhythm, and success in synchronizing. We started by evaluating scenarios with artificial rhythms, both in case of constant and variable reference cadence (Subsect. 2.2.4). In the former scenario, we tested the presence of a relationship between the suggested pace and alignment performance. The difference between stride duration suggested and participants' baseline cadence was correlated with the time required to synchronize with the external stimuli, and with the percentage of task time during which the participants' stride duration was comparable with the haptic stimulation period. Since synchronization percentages values were not normally distributed, we resorted to Spearman's correlation tests, while Pearson's test was used for time to alignment. The tests revealed no significant relationship of baseline both with time ($p = 0.22$) and alignment percentage ($p = 0.86$). For what concerns the 'Artificial Leader' data, the considered values were not normally distributed so Spearman's rank-order correlation tests were run to assess the relationship between baseline and performance. Results of the tests show that there was no statistically significant correlation between comfortable stride duration and percentage ($p = 0.117$). Similarly, there was no statistically significant correlation between baseline and time for alignment ($p = 0.794$).

This result is not surprising, because the displayed stride duration was not constant and was updated every 30 s in the range going from 900 to 1100 ms/stride. In fact, this experiment was aimed to assess the behaviour of participants when facing cadences varying in a wide range. The fact that all participants managed to align to the external rhythm with no dependence on the baseline gait parameters may prove that, as long as the suggested cadence is selected inside a feasible range, the user can successfully adapt his own walking pace. The time to achieve the alignment instead was calculated as the sum of the synchronization time after each cadence variation, thus it accounts for the randomness factor.

Then we took into consideration the social aspect and the users' response in following another human. Outcomes from the Human Leader and Peer-to-peer experiments were analyzed (Subsect. 2.2.4). For what concern the 'Human leader' scenario, we evaluated the relationship between the time to reach the synchronization, the percentage of the trial during which the follower was aligned with the leader, and the difference between leader's and follower's stride duration. All the considered variables were normally distributed, as assessed by Shapiro-Wilk's test (difference $p = 0.391$, alignment percentage $p = 0.164$, and time to alignment $p = 0.965$). The Pearson's product-moment correlation revealed no significant correlation between walking pace difference and alignment percentage ($p = 0.128$). On the contrary, Pearson's product-moment correlation between initial stride duration difference and time to alignment was statistically significant ($r = 0.714$, $p = 0.02$).

As in the 'Artificial Leader' experiment, the lack of relationship between baseline cadence and alignment performance may imply that the self-selected pace does not affect the synchronization percentage. On the other hand, the significant correlation of baseline pace with the alignment time may be due to the fact that accommodating to a farther rhythm takes longer. This aspect is interesting on the perspective of defining effective strategies to facilitate the alignment between two or more participants: instead of providing the raw partner's cadence, it may be smoothed to avoid oscillations during transient.

Similar results were collected for data in the peer-to-peer experiment (Subsect. 2.2.4). The same metrics were exploited to evaluate the correlation between users' pace and performance. Shapiro-wilk's test assessed normality distribution for stride duration difference ($p = 0.255$), alignment percentage ($p = 0.546$), and time to achieve alignment ($p = 0.249$). Pearson's product-moment correlation revealed no statistically significant relationship between the difference in initial gait cadence and alignment percentage ($p = 0.081$), neither between cadence deviance and time to reach the common stride duration ($p = 0.263$). While the former result is in line with the one obtained from Human Leader data, the latter is in contrast. Further experiments are required to address this matter, but we hypothesize that the two participants' efforts in aligning their cadence may generate non-linear dynamics.

2.2.6 Qualitative results and users' feedback

Similarly to [97], at the end of the peer-to-peer experiment participants were asked to fill a questionnaire comprising four multiple-choice and one open question about personal impressions and suggestions. The aim of the questionnaire was investigating the effectiveness of the system with a qualitative approach.

It is worth pointing out that all the subjects involved in the survey participated in at least two experiments (they were not naive to haptic stimulation for cadence regulation). The first question was about the spontaneity in aligning to the external rhythm provided by the haptics. With the second question we evaluated the ease of use of the vibro-tactile anklets. The following topic under investigation was the social side of the proposed work: we asked subjects' opinion on the system transparency, *i.e.*, whether the stimulation resembles a human walking cadence. Finally, we evaluated the impressions of walking with a remote companion.

The list of questions is reported in the following.

Q1:	*Did aligning to the vibrations come naturally to you?*
Q2:	*Could you align with ease to the rhythm received?*
Q3:	*Do you think that the vibrations you received could be associated to a human walking cadence?*
Q4:	*Did you perceive your partner's telepresence?*

Answers were entered on a Likert scale with range 1-7, where 1 represented 'Strongly Disagree', and 7 'Fully Agree'.

Results Answers to the questionnaires are reported in what follows in terms of mean ± standard deviation. The subjects' average ratings were 4.3 ± 1.5, 4.8 ± 1.3, 5.7± 1.1, and 5.9 ± 1.1, respectively for questions Q1, Q2, Q3, and Q4. A graphical representation of the users' answers is reported in Fig. 2.15.

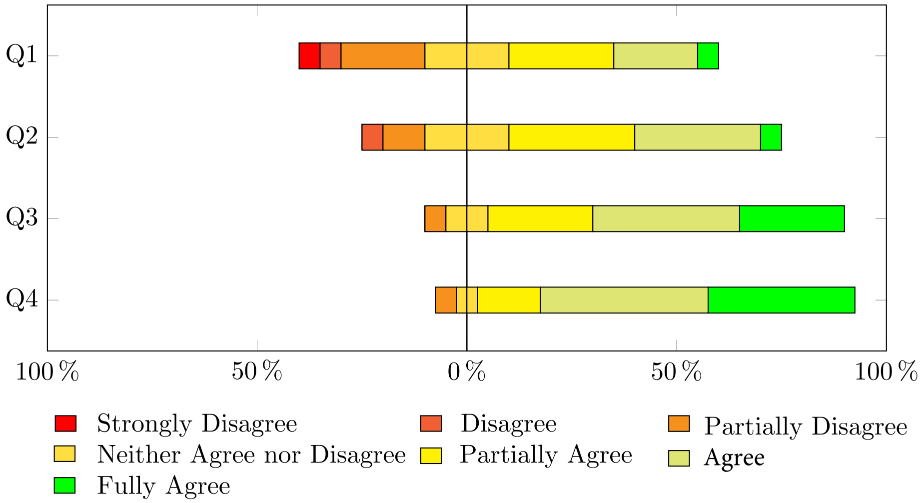


Figure 2.15: Average questionnaire scores. For each question the distribution of answers is reported.

Discussion The analysis of the multiple choice questions confirms that almost all of the participants perceived the proposed system as an effective tool to transmit walking cadence. Vibrational cues are generally perceived as an easy and intuitive way to 'feel' the presence of the remote companion. Although most of the users felt the system mechanism to convey the gait cadence as natural, some did not agree on its intuitiveness. The experiments showed that the cadence alignment was achieved in every trial, even though roughly one out of four found it hard to achieve synchronization.

Moreover, the answers to the open questions revealed that not only the emotive aspect incentives the alignment, but also that synchronizing to the vibrations is satisfying.

As a conclusive assessment we evaluated the possible correlation between the users' performance and the correspondent questionnaire responses. A global score was calculated for each participant as the sum of the four questionnaire ratings. For what concerns the variation of the walking rhythm during the peer-to-peer experiment (see Table 2.6), we did not select the users' cadence variation from the baseline value, because it does not consider the partners' behaviour during the experiments. Instead, we used the difference between user's and partner's cadence variation during the task. For instance, the couple U7-U8 (Table 2.6) has an average variation of 4%, but U7 modified his cadence by 7%, while the U8's change was only 1%. On the contrary, U5 and U6 average cadence modification was 4.5%, with a slight difference among them (1%). In those cases, cadence variations were +6% and −6% respectively for U7 and U8 (obtained as $variation_{U7} - variation_{U8}$ and $variation_{U8} - variation_{U7}$), and −1% and +1% for U5 and U6.

Firstly, we assessed through the Shapiro-Wilk's test the normality of data. While the users' ratings and the percentage variations of the user' gait were normally distributed ($p = 0.358$ and $p = 0.977$), alignment percentage failed Shapiro-Wilk's test ($p = 0.037$). Pearson's product-moment correlation was run to assess the relationship between questionnaire rates and user's cadence variation. There was a statistically significant positive correlation between percentage variation in modifying the walking cadence and answers in the survey ($r = 0.701$, $p = 0.01$). The Spearman's test between trial aligment percentage and questionnaire ratings revealed no statistically significant correlation ($p = 0.204$).

Users' rating are not linked with the task performance (*i.e.*, walking and reaching a common rhythm), as already suggested by correlational tests in the previous subsection. On the other hand, the correlation coefficient expresses a strong relationship ($r^2 = 0.49$) between questionnaire ratings and participants' relative cadence variations after the synchronization with partners. Although correlation does not imply causality, we hypothesize that participants who did accomodate to the partners' rhythm succesfully had rated their experience as positive, while users who felt uncomfortable with the haptic stimulation mainly expressed low scores. This assumption lays the basis for the next projects, were participants' behaviour will be investigated as a factor to achieve cadence alignment with multiple partners. Moreover, we need to test whether training affects the users' acceptance of our system.

2.2.7 Conclusions

Summary

In this section, a system for social remote walking was presented and incrementally tested in each of the aspects comprising its global functioning. After designing the technological parts (hardware and software), and performing engineering testing, a first experimental session confirmed that humans can follow a time varying artificial rhythm perceived via anklet vibrations. We then assessed that the tracking performances are retained when the virtual reference is replaced with a human gait cadence with a dedicated set of experiments. Finally, we obtained experimental evidence that two humans, walking simultaneously but not in each other proximity, can synchronize their gait cadence when perceiving the companion's walking rhythm using our system.

Future research directions overview

The presented results pave the way for numerous interesting research directions that will be the subject for future works. We briefly list the most attracting.

This study mainly focused on presenting the haptic system and testing its effectiveness in allowing mutual gait cadence influence in humans. Following that confirmation, we are ready to extend results to more various population including older adults.

Even if this work focused on its social aspect, the presented system may also be used by a single walker to have a personal stimulus and track a cadence profile. Such profile may come by a previous personal run, or by a friend's one; additionally it can also be prepared by a personal trainer. In a similar fashion, rehabilitation scenarios can be designed so that patients can exercise under supervision.

In presence of relevant differences in height or training condition, the synchronization may be difficult to achieve. In this case, it would be wise to investigate whether a scale factor would help to agree a common, even if different, walking cadence while retaining the feeling of walking together. Note that gait using a scale factor is not feasible while walking side by side.

Our study can be extended to a group of more than two humans. Game Theory provides numerous models that could potentially be suitable for the interpretation of the occurring group dynamics. Among the relevant indexes the synchronization and consensus of gait cadence are the most attracting.

One may also investigate different strategies to display information though vibrations, or new algorithms to facilitate synchronization (for two or more users) tailored on scenarios.

Finally, we believe that our results on remote social walking can be extended to jogging and running.

2.3 Human Rendezvous via Haptic Suggestions

This section presents an application designed for a demo-session at the AsiaHaptics 2018 conference, that leverages the results of the previous studies on haptic stimulation to suggest step frequency to participants. In this case, in addition to timing information, further haptic patterns are provided to the users for indicating the direction to the target location. In this work we propose a wearable system to guide humans in structured or unstructured environments, with the aim of reaching simultaneously a rendezvous point. Participants are provided with directional and rhythmic cues using wearable haptic interfaces placed at the subject's ankles. The walking pace guidance is achieved through the synchronization of the user's step cadence with the rhythm suggested by tactile cues.

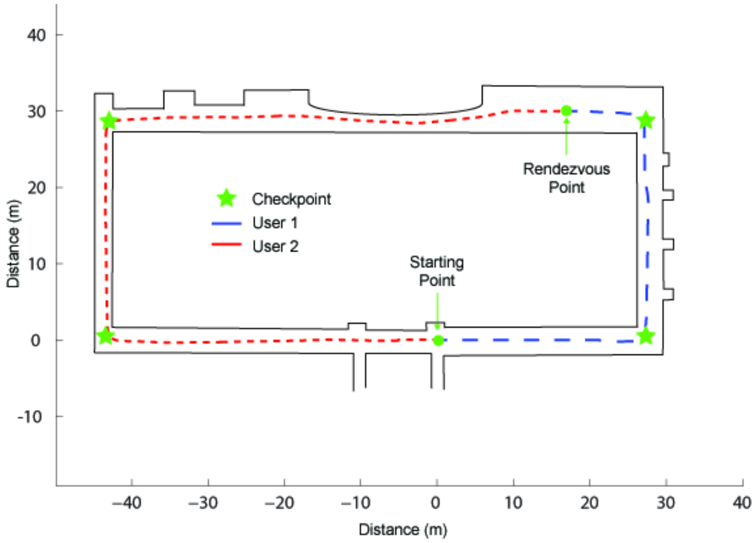


Figure 2.16: Cadence is suggested to the users using two vibro-tactile elastic bands placed on the ankles. To reach a predefined point at the same time, users have to adapt their walking pace to the one displayed by the haptic interfaces. The rhythm is updated at specific points in the map, called *checkpoints*. The users are also provided with direction information through repeated vibrations in the steering side. In this representative scenario, *User1* is closer to the goal than *User2*. To reach the rendezvous point at the same time, *User1* has to keep a slow pace, while *User2* has to increase the walking cadence. Different rhythms are depicted with different spacing in the dashed line representing the users' path. In this example, *checkpoints* are defined at every corner.

Directional hints are conveyed using different vibro-tactile patterns when the users reach predefined locations called *checkpoints*. The measurements recorded before reaching each checkpoints are used to correct the estimation of the participants' walking parameters (*e.g.* comfortable cadence and stride length) and to update the frequency of the walking pace provided by the haptic interfaces to promote the simoultaneous reaching of the target destination. The user retains complete access to audio and visual information from the environment, thus he/she is ready to react to unexpected events (*e.g.*, moving obstacles). Exploitation of the proposed approach are for instance assistive and rescue scenarios, and human-human collaboration.

2.3.1 Motivation

Human body guidance is exploited in several contexts, ranging from rescue procedures to training and rehabilitation [62–64]. Novel and promising technologies allow to track and guide individual limbs, as well as complex movements requiring high coordination [98, 99].

In this work, we focus on the fundamental human activity of locomotion. In particular, we want to address the problem of guiding humans in structured and unstructured environments. The aim is suggesting walking pace to multiple users to reach the goal destination at the same time.

Over the years, haptic stimuli have been found an effective, yet non-intrusive way for suggesting directions and pace cues to users [27, 67]. They represent an interesting way to provide information when audio and visual modalities are not available or overloaded (*e.g.*, vision is temporarily impaired).

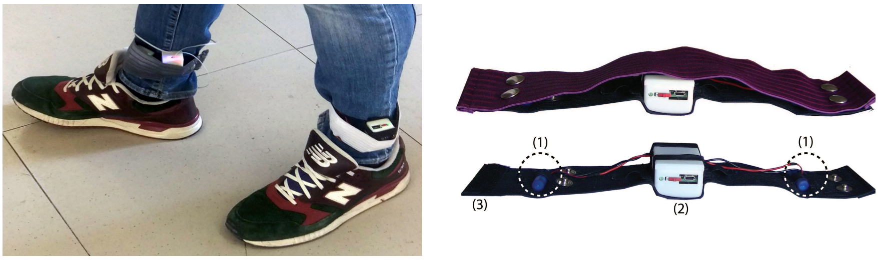
A representative scenario of the idea is depicted in Fig. 2.16, where two participants (*User1* and *User2*) are guided, by means of haptic interfaces, to reach at the same time a shared goal location.

Our method exploits the neural entrainment mechanism to suggest a specific walking cadence [60, 61]. 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.

We showed in our previous work [93] that subjects can adapt to the rhythm provided by the haptic interfaces without overloading other sensory input channels (visual and auditory). The experimental results suggested that participants preferred to receive the vibrotactile stimulation on the ankles rather than at the wrists, because the proximity of the haptic stimulus with the foot during the heel strike let subjects synchronize more easily with the external rhythm.

2.3.2 System overview

The desired cadence is suggested to the users through rhythmic vibrations provided by remotely-controlled elastic haptic bands (Fig. 2.17). Each wearable haptic interface is composed by two water-proof vibro-motors. Whenever a trigger is sent to a haptic device, the motors vibrate for 0.1s at a frequency of 250Hz, delivering a haptic stimulus to the wearer. The vibration frequency has been selected with respect to the user's maximal sensitivity, achieved around 200-300Hz [72]. A pressure sensor is placed under the right heel to detect contact with ground and to count the number of steps. The step detection is necessary for post-experimental analysis, and is a valid tool to update walking parameters (*i.e.*, the estimated step-length) in unstructured environments. An ad-hoc algo-



(a) (b)

Figure 2.17: Cadence cues are provided to the users via two vibro-tactile elastic bands placed on the ankles (a). 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).

rithm is used to control the haptic interfaces through external devices (laptop, smartphone). Information about the path and the time to complete the rendezvous are entered to calibrate the system. The communication is realized with an RN-42 Bluetooth antenna connected to a 3.3V ATmega328 microcontroller, which is also in charge of the motors activation and timing.

2.3.3 Experimental procedures

Before starting the experiment, the subjects' average stride length at comfortable cadence is estimated. Although the stride length of each individual varies with to the walking velocity [25], the baseline value at the comfortable cadence is used to initialize the rendezvous problem. The operators select two paths toward the meeting point and define the checkpoints. As a rule of thumb, checkpoints are placed in forks where the users are required to change their walking direction. The time to reach the rendezvous point is defined in accordance with the users' estimated stride length and their average comfortable cadence.

In a structured environment the tracking of the users along the path can be achieved using several techniques: optical tracking, RGB cameras, RFID technology, etc. Hence, the arrival to checkpoints is monitored automatically by the algorithm, that computes the remaining time and distance, and updates the displayed cadence for each user.

Before the trial, the users are asked to stand on the different starting points. The beginning of the trial is displayed through the simoultaneous vibrations of the two haptic anklets. The users are instructed to synchronize their steps to the rhythm displayed by the vibrations. Whenever the user reaches a checkpoint, her/his haptic interfaces stop vibrating for 1s, then display the direction toward the next checkpoint. Three different patterns are available:

go straight the two haptic interfaces are simoultaneously activated two times

turn left the haptic interface worn on the left leg vibrates twice

turn right the haptic interface worn on the right leg vibrates twice

After the direction to the next checkpoint has been displayed, the system updates the necessary stride duration to reach the destination on time, and activates the haptic interfaces according to the new rhythm. Please note that the two participants do not reach the checkpoints synchronously, thus the cadence update for the two participants happens in different time instants. The new reference cadence is estimated considering the time spent by the participant to reach the actual checkpoint from the previous one, and the distance walked (that is known *a priori*). Considering the amount of steps walked from the previous to the actual checkpoint, the algorithm estimates the stride length (that can change with the walking velocity) and the required amount of steps to reach the next checkpoint. Then, the stride duration necessary to reach the next checkpoint in time is calculated to activate the haptic interfaces. Moreover, the progress of the two users along the path are updated at every checkpoint. If one user has fallen behind, the algorithm computes a new arrival time according to the stride duration, stride length and remaining distance of the user left behind. Then, the algorithm recalculates suggested pace for the user ahead in the path, that will be updated on his next checkpoint. The trial ends when both users reach the rendezvous point.

2.3.4 Live demonstration

This scenario was designed for a live demo-session at the AsiaHaptics 2018 conference. Due to the lack of structured environment and limited space, we decided to adopt the Wizard-of-Oz approach: the operators provided instructions from remote, but the users were not aware that the experiment was piloted by humans [100]. During the demonstrations, two volunteers at time performed the rendezvous trial along two paths of different length (about 100m and 130m for the shorter and longer path, respectively). The asymmetry of the walking routes determined a different average walking cadence required for the user to reach in time the final location. The participants' stride length also affected the suggested cadence. Before the trial, subjects were asked to walk a 30 meters pathway at their comfortable speed, to estimate the subject's average stride length and stride duration. According to these parameters, the algorithm tuned the reference cadence displayed by the haptic interfaces to each participant. An operator was in charge of monitoring the progress of the trial and provide inputs to the ad-hoc software whenever a checkpoint was reached by one of the users. After reaching each checkpoint, the user's stride length was estimated on the basis of the number of steps walked from the last checkpoint (the distance was known *a priori*), and the reference cadence was updated. Due to the sequential update at every checkpoint, the variability of the suggested cadence along the trial depended on the subjects' synchronization capability: low synchronization error determined a stable reference cadence along the entire path, while bad synchronization resulted in bigger cadence variations. The performance metric used in the experiment was simple and fairly visible: the difference in time between the two arrivals to the meeting point.

2.3.5 Discussion

Although no quantitative result is reported, we list some features highlighted by the trials during the demo session. Almost all the participants managed to complete the route, reaching the final point in similar times. The asymmetry of the course has determined the need to suggest different cadences to the users in order for them to reach the final goal at the same time. In particular, often (based on step length) the user of the shorter path received a reference pace slower than their comfortable cadence, while a faster cadence was communicated for the longer path. For the success of the trial, a training phase was necessary, in order to get the participants used to synchronizing walking with haptic stimuli. It is certainly important that users understand the expected synchronization mechanism: the neural entrianment exploits the knowledge of the external rhythm to predict the 'next beat', *i.e.* internalize the tempo of the reference in order to predict the next occurrence, and adapt the cyclic movement so that it happens. In simplified terms, it is not enough to move one leg forward when receiving a trigger (vibration on the same leg), but to achieve good performance the leg must already be on the point of performing the heel-strike when the user receives the vibration. In fact, the inertia of the body introduces a delay in the 'trigger' approach that is avoided through the neural entrainment approach. The average comfortable stride duration, as already reported in literature, was about 1 stride/s. As long as the two users followed the suggested tempo with good precision, the stride duration suggested was in the range 0.95-1.15 stride/s, and all the users managed to follow said tempo. However, participants felt uncomfortable walking at stride durations greater than 1.3 stride/s (too slow) or lesser than 0.9-0.85 stride/s (too fast). The faster cadence accessible by each person is strictly variable, and probably depended on many factors: height, athleticism, age, *etc.* On average, the stride duration should not be lower than 0.9 stride/s to provide a comfortable experience to participants. In case the required stride duration to reach the target on time becomes smaller than 0.9 stride/s, it would be preferrable to extend the arrival time and provide a slower cadence to the other participant, that in turn can shorten her/his stride length to match the required walking speed without reducing the cadence too much.

Anyway we believe that the most important aspect in this application was giving to the users enough time to practice before the trial. The majority of people are naive to haptic stimulation, and are not used to align frequency and phase of walking to external rhythms (especially if the tempo is fast). Performing the trial without training is very difficult for the users, as they spend a lot of time into adapting to the initial rhythm and cannot properly complete the rendezvous in time.

2.3.6 Conclusions

This section presents an application of the haptic technology to provide timing and directional information to humans for a navigation task. The experimental protocol has been designed to test the capability of the system in displaying relevant information, and of the human participants in leveraging the information conveyed through the tactile channel to reach the rendezvous point in time. It represents one of the possible application of the haptic stimulation for locomotion studied during the Ph.D. progress. The algorithm relies on information such as path length and subjects' locomotion parameters to estimate the adequate cadence and provide it to the user through vibro-tactile interfaces placed at the user's ankles. The users have to adapt their walking pace to the one suggested by the haptic interfaces. The rhythm is updated at specific points, called *checkpoints*, where the user also receives direction information through repeated vibrations in the steering side. The adoption of checkpoints, although piloted in a Wizard-of-Oz approach during the demo session, allowed the users to complete the task. It may represent a smart solution for human navigation in unstructured environments, *e.g.* by using RFID technology to detect the arrival at the checkpoint for the path update. In future works, we will further investigate the dependence of users' stride length from the suggested cadence, and how to optimize the tempo of haptic cues accordingly.

Chapter 3

Guidance for Human-Human Cooperation

The research projects on human locomotion assessed the capabilities of wearable haptic technology in providing the users with relevant task information. The haptic guidance of human walking cadence is possible thank to a mechanism called neural entrainment, that our body exploits to match motion tempo to external rhythms.

This Chapter introduces a different side of human guidance, geared toward collective tasks. We considered the case of a formation of humans that perform a manual task instructed through haptic stimuli. Particular emphasis is devoted to the design of haptic patterns to instruct the formation, that need to deliver the necessary information without overloading the users. The experimental discussions pave the way toward the definition of guidelines for the design of haptic patterns to augment the human perceptions in individual and collaborative tasks.

3.1 Design and Comparison of Haptic Guidance Policies

This section investigates the use of tactile stimuli to guide users in a Human-Human collaboration scenario, specifically a formation of humans carrying a bulky object. Since the aim of the work is understanding the bases of haptic stimulation design for humans, we defined three guidance conditions that are tested in the experimental trials to evaluate pros and cons of each approach: *i)* guidance based on Holonomic walking model, *ii)* guidance based on Nonholonomic walking model, and *iii)* a Sensory Augmentation approach. Five couples of blindfolded participants performed the object-loading task under the three haptic policies. The formation and the object were tracked by means of RGB cameras and ArUco markers. The metrics evaluated are *i)* smoothness of walked trajectories, *ii)* task completion time and *iii)* subjective evaluations through a questionnaire on usability, intuitiveness and comfort. The experimental and subjective results revealed that using the haptic policies to provide the users with relevant information on the task, *i.e.* the direction to the goal, was the most efficacious factor for achieving time-effectiveness, smoothness of the walked trajectories and intuitiveness of the haptic patterns. Providing strict instructions was detrimental from the point of view of the trajectory smoothness, that might represent the steady flow of the task. Conversely, the instruction-based guidance could be preferred in controlling a larger formation, or in any scenario that requires accurate movements.

3.1.1 Motivation

Human physical interaction happens when two (or more) people jointly perform a task like carrying a bulky object, teaching manual skills, or dancing together. Such tasks require participants to predict, react, and adapt to each others' forces and to synchronize motions. Very often it happens in the absence of any explicit verbal or visual communication and users may be connected only by tactile feedback, *e.g.* via a mutually grasped object.

Recent research trends are exploring the innovative field of human cooperation mediated by robots, where a formation of two or more individuals performs a complex task by sharing information through robotic aids rather than directly [101]. The crucial role of robotic interfaces in the context of human cooperation is indeed to provide a robust detection of co-workers' actions, and to broadcast information about the operators and the environment to the rest of the group, so to facilitate the coordinated task. For instance, recordings of tactile interaction have been used to detect and classify interaction states between human operators in physical Human-Human cooperation [102], *e.g.* relying on force and torque data measured on the grasped object [103].

Now, let us focus on the problem of guiding humans during the transportation of an object toward a goal location in a structured environment. Handling bulky and heavy objects represents a relevant and deeply investigated area in the field of human-human and human-robot interaction. A wide range of aspects has been broadly analyzed, from lifting and moving objects with different policies for effort sharing and optimal load sharing [104, 105], to examination of different contact models [106]. In the aforementioned scenarios, robots participate to the task alongside humans, so to blend the expertise and advantages of both.

Figure 3.1: A couple of blindfolded co-workers carries a bulky object to the target point guided by haptic stimuli. Their position is tracked through fiducial markers and smartphone cameras. The guidance exploits three different haptic policies, whose performance are compared in the experimental campaign.

Paradigmatic examples are represented by shared-control and mixed initiative approaches [107, 108].

However, there exist some situations where it is not possible or it is risky to have robots assisting humans in handling objects (*e.g.*, bumpy paths, narrow passages through stairs, *etc.*), and the environment could not permit any audio or visual communication between humans. In such situations guaranteeing the operators' safety is a priority. Indeed, in 2018, there were 3.1 million non-fatal accidents at work, the most common causes included transport and handling equipment (20.9% of the total) [109]. Human collaboration can be improved by enriching users' knowledge on the current task or by providing environmental awareness. To this end, haptic feedback has been found an effective, yet non-intrusive way for providing informative cues to users, like direction, boundaries proximity, payload overreaching, *etc.*, without overloading or impairing hearing and vision. Some examples from scientific literature are listed as follows. A vibrotactile waist belt composed of eight tactors was designed for waypoint navigation in outdoor scenarios [64]. The waist belt displayed both the direction and distance to the next waypoint. In [67] a couple of vibrotactile bracelet was adopted for human guidance in indoor environments. Vibrotactile stimuli displayed directional hints to the blindfolded users. Similarly, haptic armbands were used to provide environmental information during a wheelchair driving task in [110]. Participants achieved better performance when informed about path obstacles,