Cruise Control for Pedestrians: Controlling Walking Direction using Electrical Muscle Stimulation

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ABSTRACT
Pedestrian navigation systems require users to perceive, interpret, and react to navigation information. This can tax cognition as navigation information competes with information from the real world. We propose *actuated navigation*, a new kind of pedestrian navigation in which the user does not need to attend to the navigation task at all. An actuation signal is directly sent to the human motor system to influence walking direction. To achieve this goal we stimulate the sartorius muscle using electrical muscle stimulation. The rotation occurs during the swing phase of the leg and can easily be counteracted. The user therefore stays in control. We discuss the properties of actuated navigation and present a lab study on identifying basic parameters of the technique as well as an outdoor study in a park. The results show that our approach changes a user's walking direction by about 16°/m on average and that the system can successfully steer users in a park with crowded areas, distractions, obstacles, and uneven ground.

Author Keywords
Pedestrian navigation; electrical muscle stimulation; haptic feedback; actuated navigation; wearable devices

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation: User Interfaces – Input devices and strategies; Haptic I/O.

INTRODUCTION
Navigation systems have become ubiquitous. While today we use them mainly as commercial products in our cars and on our smartphones, research prototypes include navigation systems that are integrated with belts [22] or wristbands [10]. These systems provide explicit navigation cues, ranging from visual feedback (e.g., on a phone screen) via audio feedback (e.g., a voice telling the direction in which to walk) to tactile feedback (e.g., indicating the direction with vibration motors on the left or right side of a belt).

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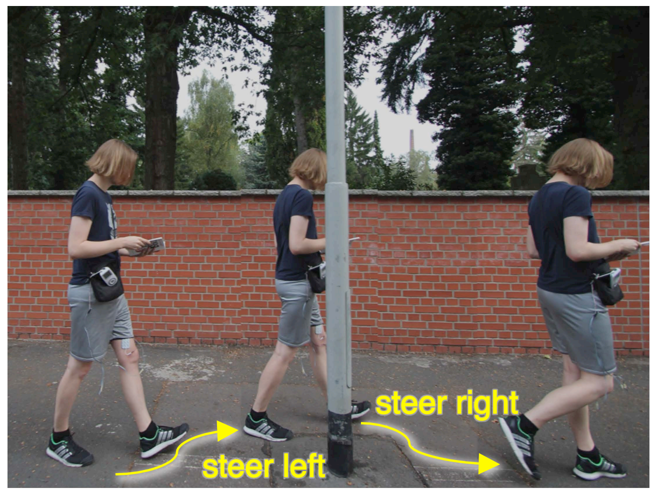

Figure 1. A user is absorbed in his reading, not noticing the lamppost. Actuated navigation automatically steers him around the obstacle.

An obvious drawback of such solutions is the need for users to pay attention to navigation feedback, process this information, and transform it into appropriate movements. Moreover, navigation information may be misinterpreted or overlooked. The need to cognitively process navigation information is particularly inconvenient in cases where the user is occupied with other primary tasks, such as listening to music, being engaged in a conversation, or observing the surroundings while walking through the city. To avoid intrusions into the primary task we envision future navigation systems to guide users in a more casual [17] manner that, in the best case, does not even make them aware of being guided on their way.

As a new kind of pedestrian navigation paradigm that primarily addresses the human motor system rather than cognition, we propose the concept of *actuated navigation*. Instead of delivering navigation *information*, we provide an *actuation* signal that is processed directly by the human locomotion system and affects a change of direction. In this way, actuated navigation may free cognitive resources, such that users ideally do not need to attend to the navigation task at all.

In this paper we take a first step towards realizing this vision by presenting a prototype based on electrical muscle stimulation (EMS) to guide users. In particular, we apply actuation signals to the sartorius muscles in the upper legs in a way such that the user slightly turns in a certain direction. With our system the user stays in control or can give it away: The system does not cause walking movements, but only slightly rotates the leg in a certain direction while the user is actively walking. The user can easily overwrite the direction by turning the leg. If the user stops, the system does not have any observable effect, as the EMS signal is not strong enough to rotate the leg when the foot is resting on the ground.

The contribution of this work is twofold. First, we introduce the notion of actuated navigation and present a prototype implementation based on electrical muscle stimulation. Second, we present findings of (a) a controlled experiment to understand how walking direction can be controlled using EMS and (b) a complementary outdoor study that explores the potential of the approach in an ecologically valid setting.

In the following, we discuss the properties of actuated navigation and present the two studies in detail. The results show that our approach can successfully modify a user's walking direction while maintaining a comfortable level of EMS. We found an average of 15.8°/m deviation to the left and 15.9°/m deviation to the right, respectively. The outdoor study shows that the system can successfully steer users in a park with crowded areas, distractions, obstacles, and uneven ground. Participants did not make navigation errors and their feedback revealed that they were surprised how well it worked.

RELATED WORK

We draw upon related work that uses novel output modalities for pedestrian navigation systems, in particular tactile feedback. In addition to that, we present work on Electrical Muscle Stimulation (EMS) that is applied to (a) provide tactile feedback to the user and (b) stimulate the muscle resulting in movement. Moreover, we discuss options for actuating muscles to modify the walking direction.

Pedestrian Navigation

Pedestrian navigation systems and mobile city guides have been widely researched in the past [1], with a focus on how to present rich map information on small displays and how to support the user in matching the current position and orientation to the displayed information. Approaches include providing photorealistic panoramic images from 3D city models rather than symbolic 2D map data [14], automatically rotating virtual maps to correspond to the user's orientation in the real world [19], and coupling paper maps to virtual information using mobile augmented reality approaches [15].

It is widely recognized in the literature that navigation and wayfinding tasks can put a high cognitive workload on users and distract from the environment. Reducing workload and distraction are prime concerns of pedestrian navigation systems [7, 14, 16] and are the main motivation for our work.

Tactile and Haptic Navigation

To reduce the reliance on the visual and auditory modalities, particularly as users engage with processing cues from the physical surroundings, vibration feedback has been suggested as an alternative. Jacob et al. present feedback on the mobile phone as soon as it is pointed to the correct direction [9]. However, this requires active exploration of the surroundings to enable guidance. Pielot et al. developed a haptic compass for off-the-shelf mobile phones worn in the pocket [16]. The target direction is encoded with a two-pulse vibration pattern. NaviRadar [18] is able to communicate arbitrary directions around the user based on a radar sweep metaphor. Another approach is to present the direction by applying vibration feedback to a specific position on the body. Users then map the body position to the direction they need to take. This has, for instance, been done with two vibrating wristbands [10]. To provide directional information, Tsukada and Yasumura [22] used a belt containing eight vibrators equally spaced around the user's torso. The system activates the vibrator that matches the target direction. To achieve more fine-grained direction indication Heuten et al. [7] extended this approach and developed a spatially continuous tactile display by interpolating the intensity between adjacent vibrators.

Haptic navigation systems generate a force to convey direction. Amemiya and Sugiyama [2] built a handheld indicator that provides direction cues to the user via a pseudo-attraction force. The force is generated by a linear micro-actuator that moves a weight quickly in the navigation direction. It then moves back slowly such that the user does not sense it. HapMap [8] also displays direction haptically: A servomotor in a handheld casing (formed like a piece of handrail) tilts right or left to generate a perceivable torque. Pull-Navi [11] is a head-mounted device that communicates direction by pulling the ears in 3D. PossessedHand [21] actuates the hand to indicate walking direction haptically.

Augmented Walking

Active manipulation of walking has been explored for navigation and to enhance the walking experience. Gilded Gait [20] aims at simulating different ground textures by providing tactile feedback through multiple vibrators embedded in insoles. The user can perceive deviations from the path through modified or missing tactile feedback. CabBoots [5] is an experimental system that tilts the soles of shoes to guide the user left or right. This approach requires relatively strong actuation forces and mechanics to achieve tilting.

Most closely related to our idea are Fitzpatrick et al. [4] and Maeda et al. [13] who manipulate the user's sense of balance through galvanic vestibular stimulation (GVS). By applying GVS, the vestibular system is disturbed so that the user automatically sways in a specific direction. In this approach, a small DC voltage is applied between the mastoid processes (positioned behind the ears) such that a current of 0.5-1.0 mA results. This leads to a decreased firing rate in vestibular afferents on the anodal side. GVS lets people sway towards the anode. GVS modifies human behavior directly. No attention is required. GVS can be used to modify walking direction. However, it has been found that visual input overrides vestibular disturbances [4]. The latter report walking experiments from a starting position towards a target with eyes open and shut. In contrast to our approach, GVS effects the sense of balance and mainly effects swaying the upper body in a particular direction, whereas our approach actuates human muscles and effects a leg rotation in a particular direction. Except for

GVS, the presented approaches require the user to perceive, interpret, and react on the output of the navigation system. In contrast, we propose to actuate the human locomotion system via EMS directly, such that the user does not need to concentrate on the navigation task.

Electrical Muscle Stimulation

Electrical muscle stimulation (EMS) delivers a weak electrical signal to the muscles. In our work, we use non-invasive surface electrodes, which are placed on the skin. The electrical signal elicits action potentials on motor nerves, which control muscle fibers. Stimulating the motor nerves leads to contraction of the muscle fibers. Using appropriate patterns, weak EMS can generate feedback similar to vibration.

EMS has a long tradition in rehabilitation engineering under the term functional electrical stimulation (FES) [23]. The goal of FES is to restore motor functions of paralyzed patients. With respect to the lower limbs there has been work on correcting foot drop, which denotes the inability to raise the forefoot. A proposed treatment is to apply EMS to muscles at the front of the tibia during the swing phase of gait to flex the forefoot, synchronized by a heel-switch [12]. Other applications with regard to the lower limbs include knee joints movement, cycling, standing up, keeping body balance, and walking (see [23] for a review). For the latter three tasks, research is still at the simulation stage. Controlling walking, for example, is an extremely difficult task because many independent muscles have to be controlled in a coordinated way and a joint may have multiple degrees of freedom. Moreover, the muscles respond in nonlinear and time-varying ways to electrical stimulation such that closed-loop solutions are necessary. Further problems are time delays between signal and response and muscle fatigue. EMS, particularly when applied through surface electrodes, has different characteristics than voluntary control signals, which leads to rapid fatigue. Moreover, not all of the muscles in the lower body are accessible or can be selectively activated when using surface electrodes.

Significant research effort went into restoring gait, which requires to selectively stimulate multiple muscles in the affected leg [3]. A simpler task than complete artificial control of lower limbs is to correct gait of partially impaired patients. EMS has been used for faster recovery and to improve gait.

In our work we do not attempt to fully control walking. Our goal is just to influence the direction of walking. This involves an outwards rotation of the leg that corresponds to the intended walking direction [6]. For example, if the human intends to go to the right, one part of turning is that the right leg is slightly rotated outwards. The actual rotation happens in the swing phase of the leg, so that the foot that is put on the ground points into the new direction.

To achieve the same effect with EMS, we first identified the muscles that lead to an outward rotation of the leg. A number of muscles are involved in this activity [6]: m. gluteus maximus (intimate), dorsal parts of the small glutei medius / minimus (intimate), m. quadratus femoris (intimate), m. gemelli (intimate), m. obturatorius internus (deep), m. obturatorius externus (deep), m. piriformis (intimate), m. iliopsoas (deep), and m. sartorius. Unfortunately, except for the musculus sartorius, all of these muscles are either inacessible for electrode pads, because they are deeply embedded in tissue, or are partially located in intimate zones of the body. We thus focus on the sartorius (Figure 1), which is a long and thin muscle that runs across the upper and anterior part of the thigh. It is connected to the pelvis and to the upper tibia. Contraction of the sartorius leads to flexion of the hip and the knee joints. Stimulating it electrically while walking leads to lateral rotation of the leg and therefore to a change of the walking direction.

Another possibility of modifying the walking direction would be to shorten the step length on the side in which to rotate. To achieve this, EMS could be used to block the large muscles on the front and back side of the thigh. Yet, this will likely impact on gait stability, which is why we leave exploring this opportunity for future work.

Prior research that exploited EMS for pedestrian navigation includes the work of Tamaki et al. [21], who control the user's hand to indicate walking direction.

PEDESTRIAN NAVIGATION THROUGH ACTUATION

Pedestrian navigation systems sense the position and orientation of the user and give directions to guide the user towards a goal or along a route. There are a number of different options of how to convey navigation information to the user that we discuss in the following.

Classification of Navigation Systems

The most widely used modalities are *visual and auditory* output (Figure 2a). Here, symbolic information, like arrows overlaid on a map or verbal instructions, are presented to the user. This information can be more or less abstract, but has to be perceived and interpreted before the appropriate motor commands can be issued. Interpretation often involves mapping the symbolic instructions to the real world. Although the visual and auditory senses have a high bandwidth they are typically already engaged with acquiring information from the world around the user, and the additional navigation information interferes with this real world information.

To shift perceptual load off the visual and auditory senses, *tactile navigation systems* have been developed, in which, for example, vibration output is applied to different body parts to indicate points at which the user has to turn left or right (Figure 2b). The tactile channel has lower bandwidth than the visual and auditory channels, but in many cases tactile feedback at decision points along the route suffices for successful navigation. Simple vibrotactile output is limiting, however, in that it does not easily convey precise direction. Here, as in (a), the information has to be perceived and interpreted before it can be mapped to motor commands.

As shown by Tamaki et al. [21], *muscle stimulation systems* allow directional information to be conveyed, which can be used for navigation (Figure 2c). In this case, the hand is directly actuated and moved towards the target direction. The human hand is used as an output device. It serves as an indicator of the navigation direction. Still, the user has to perceive

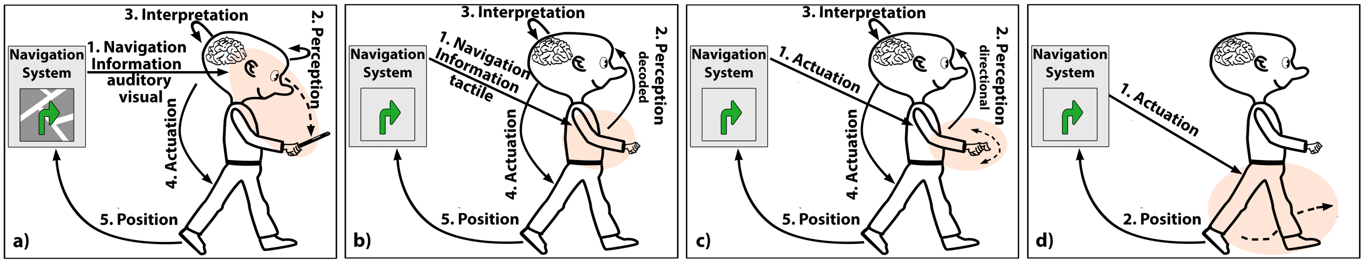

Figure 2. Pedestrian navigation using (a) visual or auditory output, (b) tactile output, (c) actuation of the hand as an indicator, and (d) direct modification of walking direction (in our case actuation of the human locomotion system).

the movement through visual and haptic channels (proprioception), interpret it, and walk into the indicated direction. Moreover, the hand cannot be placed in the pocket. Since navigation information can be easily observed by others, the concept may lead to issues with regard to privacy and social embarrassment. However, the mapping is direct and simple. The feedback is multimodal (haptic and visual) and the actuation of the hand will immediately draw the user's attention.

The option we propose is depicted in Figure 2d. Our approach is based on muscle stimulation. In this way we convey navigation information through *actuation* rather than through communicating a direction. While doing so is, in general, also possible using GVS [4] or CabBoots [5], we apply an EMS signal in such a way as to slightly modify the user's walking direction towards the target direction. Our approach directly manipulates the locomotion system of the user. We believe this approach to minimize cognitive load, since neither perception, nor interpretation, nor voluntary issuing of motor commands are necessary to adapt the direction. Still, users perceive the directional signal. If the user stops, the system output has no observable effect. Moreover, the signal is weak enough that the user can override it and walk in a different direction if desired. The navigation signal cannot be observed by others as it is delivered privately to the user.

This approach frees the sensory channels and cognitive capacity of the user. The user may be engaged in a conversation, observe the surrounding environment during sightseeing, or even write an SMS, and is automatically guided by the navigation system. We refer to this experience as "cruise control for pedestrians." Of course, the positioning technology has to be accurate and robust to allow for high-precision navigation. Moreover, obstacles and threats have to be reliably recognized by the system. These issues are beyond the scope of this paper. Instead we focus on the possibility to control the user while minimizing the cognitive load.

Information vs. Actuation

The fundamental difference to most prior approaches is that our solution solely relies on actuation. The information approach refers to the user's perceptual system ("input") and information processing capacity. The actuation approach primarily addresses the human motor system ("output"). Option (c) is a hybrid variant that provides information through actuation (hand movement indicating direction). With information delivery, the human cognitive system has to process the information and respond to it. The user has a higher degree of control in that the information may be ignored. On the other

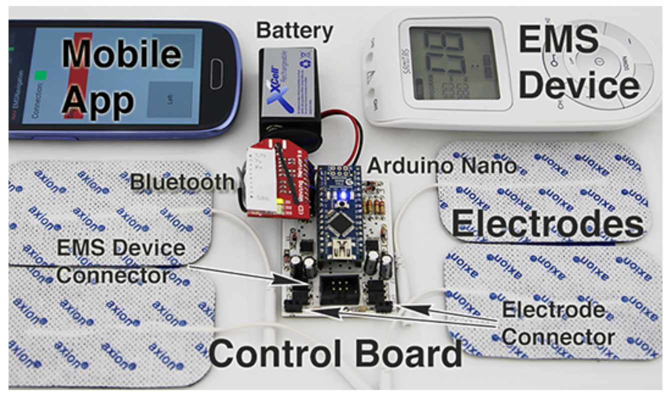

Figure 3. The hardware prototype including the EMS device, self-adhesive pads, the wireless control board, and a mobile device with control apps.

hand information can also be overlooked or misinterpreted. It is the responsibility of the system designer to make the navigation information as easily interpretable and the mapping to the task as direct and natural as possible. Moreover, the information delivered by the system may interfere with other information in the surroundings of the pedestrian.

In the case of delivered actuation, no cognition is required. Rather, deviating from the navigation path requires counteracting the system-generated force. Reacting flexibly to changing goals can be achieved by observing user behavior, recognizing the intent to take a different path, and resetting the navigation system accordingly – or directly communicating with the user. The result would then be a shift from automatic actuation to explicit communication and goal setting.

On-Body vs. Environmental Feedback

The device that outputs navigation information may be placed on the user or in the user's vicinity. For pedestrian navigation systems the main options are handheld or wearable devices. Handheld devices typically use the visual and auditory channels and have the additional disadvantage that they occupy the user's hands. Holding the device all the time is tiring and problematic if, for example, the user carries a bag. With handheld devices, visual output is delivered on the device screen or through a microprojection. In the latter case navigation cues may be projected on the ground. Electronic displays and especially microprojections are problematic in direct sunlight. Visual output may also be delivered via head-mounted displays. Auditory output is typically played via speakers or headphones. Tactile output requires stimulation of mechanoreceptors in the skin.

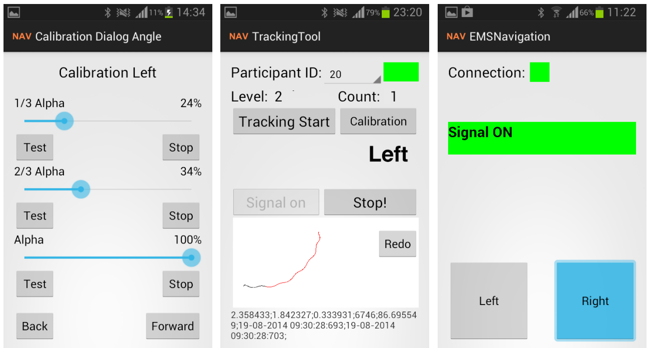

Figure 4. Apps to calibrate the user's leg (left), control a single trial in the lab study (middle), and remote-control the user's walking direction in the outdoor study (right).

Visual output has high switching costs between the real world and the navigation information on the display. Switching cost may be reduced for head-mounted displays if the virtual information is integrated with visual information from the real world, as in augmented reality systems. Auditory output has low switching costs but requires earphones for privacy, which shields the user from the surroundings to some extent. Tactile output has low switching costs and retains privacy. However, all of these options draw the full attention of the user and require a significant amount of cognitive processing.

A major advantage of on-body feedback is that it can, in general, be more easily perceived by the user. While environmental feedback needs to compete with a lot of objects in the user's field of view, on-body feedback is much less likely to interfere with other cues. As a result, users could more easily focus on the primary task. On the downside, on-body feedback requires actuators to be worn and may be more intrusive.

PROTOTYPE

To investigate the concept of actuated navigation we developed a hardware prototype that applies EMS signals to the user with different impulse forms, intensities, and activation times. It connects to a mobile phone running the usual navigation software. We developed a set of control applications to support (a) a lab experiment investigating change of direction during single walking trials, and (b) an outdoor study in which users were guided along marked and unmarked trails.

EMS Control Hardware

For generating the EMS signals we use an off-the-shelf EMS device[1] (Program 8 TENS with 120 Hz, 100 μs) with two output channels (Figure 3, top right). We use a commercial EMS device for safety reasons. A *custom control board* with an Arduino Uno, a Bluetooth module, and digital potentiometers (41HV31-5K) controls the signal of the EMS device. The board is able to switch the two channels of the EMS device on and off as well as to reduce the signal intensity in 172 steps. The board runs on a 9 V battery and has a size of $45 \times 63 \times 21$ mm. As electrodes we use 50×90 mm self-adhesive pads that are connected to the control board. The hardware prototype was designed for wearable use (Figure 3).

[1] Beurer Sanitas SEM 43 Digital EMS/TENS

Control Applications

The hardware prototype is controlled by 3 apps: (1) a calibration app, (2) a study app, and (3) a navigation app. The apps run on a Samsung Galaxy S3 Mini and are connected to the hardware prototype via Bluetooth. The apps use a custom protocol to send EMS parameters.

Calibration App. The calibration app (Figure 4, left) adjusts the strength of the applied EMS signal. We use it for calibrating and storing user-specific intensities. Furthermore, the app records current and voltage levels during the study.

Study App. Via the study app (Figure 4, middle) different user-specific settings are selected. It records precise positioning data from a Naturalpoint OptiTrack infrared tracking system. The application is also responsible for controlling the EMS hardware during the study.

Navigation App. The navigation app (Figure 4, right) serves as a remote control in the outdoor navigation study. It simply contains two buttons. As long as one of the buttons is pressed, actuation is applied and the user is steered towards the selected direction.

LAB STUDY

The goal of the lab study was to understand how to control walking direction using EMS. As other muscles that are relevant for leg rotation are either inaccessible or are located in intimate areas, we focus on the stimulation of the sartorius muscle. There are a number of parameters and characteristics that need to be identified. These include the optimal position of the EMS electrodes on the thigh, the maximum level of stimulation that still feels comfortable, and the degree of directional change during walking that can be elicited. We also aim to investigate whether different levels of stimulation can be mapped to different rotation angles. Finally, we aim to analyze whether direction control while walking has negative effects on gait, such as instability.

Participants

We recruited 18 participants (13 male, 5 female) aged between 18 and 27 (M=22.1, SD=2.3) via university mailing lists and at a sports club. According to the questionnaires, 12 of them are doing sports regularly. 10 participants regularly use pedestrian navigation systems on their phone (Google Maps, Apple Maps, and OsmAnd). All of them look onto their phone screen for navigation, one uses audio. None of the participants ever used tactile feedback for navigation. 8 of the 10 users said that navigating distracts them from other tasks, such as from traffic, from conversing with friends, from listening to music, and from talking on the phone. Five participants previously used EMS for massages, pain relief, training, participating in studies, and testing EMS out of curiosity. None of the participants used EMS regularly.

Experimental Design

The study was designed as a repeated measures experiment. The independent variables were the intensity level of the EMS actuation (strong, medium, weak, off) and the starting position of the user (left, middle, right). Users starting from the left position were guided to walk right and vice versa. The

Figure 5. Placing the pads on the musculus sartorius (left) and measuring the angle of deflection corresponding to EMS intensity (right).

starting position also determined the leg with which users started to walk (left leg for starting right and vice versa). When starting from the middle, no feedback was applied and users started once with the left leg and once with the right leg. This resulted in 3 (left position; strong, medium, weak intensity) + 3 (right position; strong, medium, weak intensity) + 2 (middle position; left leg, right leg; EMS off) = 8 conditions. Conditions were counterbalanced and repeated 5 times each, resulting in 40 trials per user. As the dependent variable we measured the user's head trajectory (position and orientation).

Setup & Procedure

As participants arrived, we provided them a consent form that they had to read and sign. Also, we explicitly told participants that they could abort the study at any time. We asked them to change before the actual study. We measured the diameter of their thigh and tested for their primary leg. They then proceeded with the calibration for the main part of the study.

First, the deviation angle and the level of voltage and current were measured. One electrode pair was attached to each leg of the participant and connected to the EMS device (Figure 5, left). The EMS signal was controlled through the mobile application described in the previous section. As the actuation is not strong enough to happen while the user is standing on the ground, but only happens during the leg's swing phase, the leg had to be able to move freely during calibration. To this end, for calibration users stood on a pedestal with one foot while holding on to a tripod with one hand (Figure 5, right). The other leg was hanging freely and did not have floor contact. The EMS signal was then applied and modified until the maximum comfortable level for the user was reached. We measured the rotation angle of the foot with the OptiTrack system and markers on the shoe.

After having determined the maximum angle and intensity, we reduced intensity to achieve 2/3 and 1/3 of the maximum angle, respectively. For example, if the maximum angle was 30°, we determined the intensity values for 10°and 20°(Figure 4, left). Both legs were calibrated independently in this way. The user-specific parameters were stored in the control application for later use in the actual study. Apart from the calibration, we measured the current and voltage for each leg and angle. To this end, the EMS system and the user were attached to a test circuit with two digital multimeters.

	Angle in degree		Voltage in V		Current in mA	
Participant	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
1	38	45	14.46	13.56	45.96	39.44
2	22	17	16.14	15.69	55.38	52.16
3	7	60	28.92	24.27	65.84	61.19
4	12	49	32.28	20.72	62.16	62.81
5	0	0	16.33	14.72	34.86	38.28
6	28	26	19.30	13.75	54.03	46.02
7	30	34	20.20	17.11	57.90	57.45
8	0	0	19.30	16.40	50.67	49.51
9	30	61	29.11	24.34	49.45	49.77
10	33	54	20.72	14.01	50.16	41.12
11	40	19	20.59	22.01	46.67	42.60
12	30	11	19.24	18.72	50.22	46.15
13	0	0	23.95	22.27	50.35	48.61
14	8	22	24.53	22.92	66.87	65.58
15	24	20	19.43	15.62	56.16	52.03
16	5	30	20.33	18.59	57.45	58.16
17	5	45	23.69	22.59	57.13	56.55
18	12	28	25.30	22.21	55.64	51.64

Table 1. Calibration angles and EMS levels with 120 Hz, 100 μs pulses.

The second part of the study constitutes the walking tasks. We set up 10 cameras in a 4×6 m tracking area. To maximize the trackable walking distance, the starting points were either on the left or on the right of one sideline. For the baseline condition (no actuation) participants started from a central position.

Participants were equipped with a tracking cap. The OptiTrack system continuously sent the 3D position of the user to the study app via WiFi at a rate of about 30 Hz. To keep participants from focusing on a point in the room and steering towards that point we blindfolded them with an eye mask. In this way, users also did not know the starting point, which could have led to an anticipation of the direction.

The EMS signal for each condition was applied using the study application. For applying signals to the left leg users were asked to start walking with the right leg and vice versa. After the third step the EMS actuation signal was applied. This procedure ensured that the signal was applied during the leg swinging period and at roughly the same position for each participant. For the baseline without actuation users started with either the right or left leg in alternating order. Finally, participants filled in a questionnaire and were debriefed.

RESULTS

Data Analysis

Quantitative results are based on an analysis of the calibration data, the walking trials, and an analysis of the direction changes. We excluded three participants during the calibration process. P5 did not feel well and aborted the study. On P8 and P13 the EMS system did not show any effect. Due to technical problems, data from P4 had to be excluded from the analysis of direction changes.

Quantitative Results

Figure 6 provides an overview of the data that were recorded during the walking trials. We used this data to quantify the effects of different levels of EMS actuation. Prior to further data analysis we smoothed the data using a Gauss filter, thus removing the deflection caused by head movement.

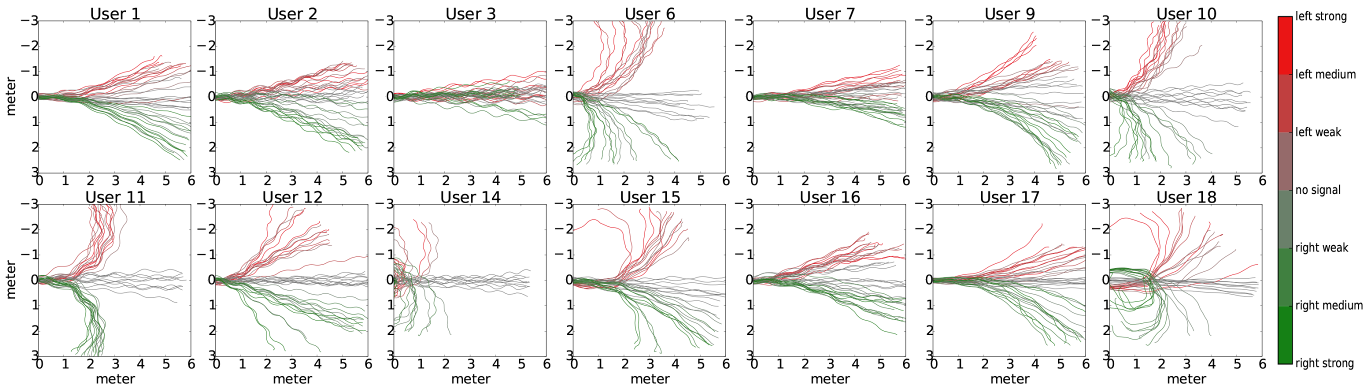

Figure 6. Plots of the raw data from all conditions and all users.

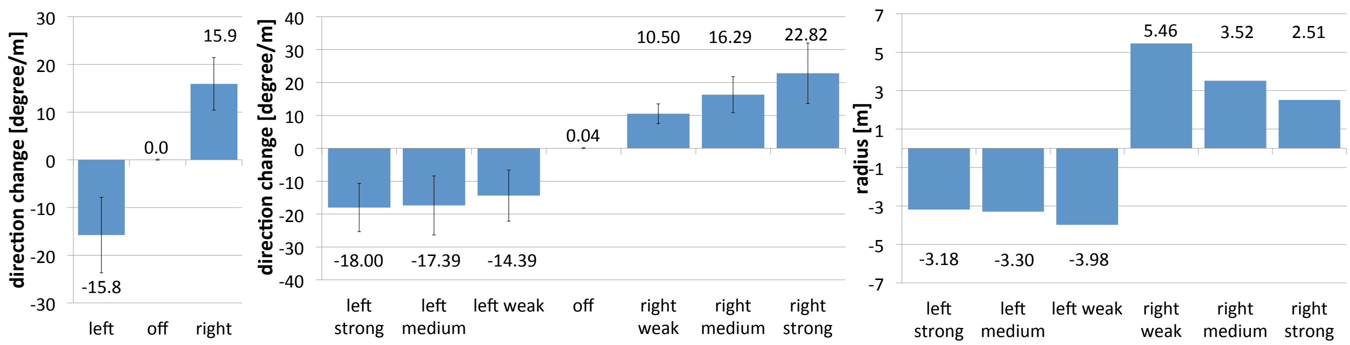

Figure 7. Direction change in degrees per meter of the overall direction (left) and divided into the different EMS level (center) as well as the respective radii (right). Error bars show standard error.

	Angle in degree/m		Radii in m	
Participant	**Left**	**Right**	**Left**	**Right**
14	-128.98	100.13	-0.44	0.57
18	-33.11	101.23	-1.73	0.57
11	-26.88	30.53	-2.13	1.88
6	-26.46	26.46	-2.17	2.17
10	-17.67	24.98	-3.24	2.29
15	-27.56	9.85	-2.08	5.82
9	-7.73	9.41	-7.41	6.09
17	-4.88	11.60	-11.74	4.94
1	-4.08	3.75	-14.05	15.30
12	-3.18	1.87	-18.04	30.60
16	-2.00	2.20	-28.65	26.04
7	-1.08	2.32	-52.96	24.67
2	-0.55	3.36	-103.74	17.05
3	-0.23	1.04	-253.61	55.02

Table 2. Directional changes and turning radii of each user.

Figure 7 shows the directional change in degrees per meter. The left graph shows an overview. The strong, medium, and weak actuation conditions have been combined for left and right, respectively. First, the median change within each user was computed, then the mean across users. The mean change is 15.8°/m to the left and 15.9°/m to the right. There is a relatively wide spread and the data are skewed towards 0°/m stemming from the fact that the actuation showed only a small effect for some of the participants. A Friedman test shows that the differences between left actuation, no actuation, and right actuation are significant on the 5%-level ($\chi^2(2)$=$24.571, p$<0.001). A post-hoc test with Bonferroni correction shows that left, off, and right are pairwise significantly different. Randomization tests on matched samples with Bonferroni correction applied come to the same result.

The center of Figure 7 shows the directional change for each condition separately. There is a tendency of stronger actuation showing larger directional change. However, again the variation is strong and does not precisely follow the calibration (which aimed for full angle at strong actuation and 2/3 and 1/3 of full angle at medium and weak actuation). Comparing all seven conditions, a Friedman test reveals a significant difference ($\chi^2(6)$=$57.245, p$<0.001). A post-hoc test finds that the left conditions are pairwise different from the right conditions and off-condition is different from the right conditions and the left conditions. There are no pairwise differences among the left conditions, and no pairwise differences among the right conditions. Randomization tests on matched samples with Bonferroni correction applied identify the same pairwise significant differences.

For steering pedestrians around corners the turning radius is relevant. As can be seen in Figure 6, while actuation is active users move on a circular path. If the tracking area had been large enough and the actuation had continued, the test participants had moved in circles. The above results relate a length of 1 m on the circle arc to a rotation of $\alpha°$. This translates into a radius r=$\frac{180}{\alpha\pi}$. The radii associated with the above direction changes are shown in Figure 7 – right. As expected, the smallest turning radii of 3.18 m for left turns and 2.51 m for right turns are associated with strong actuation. These radii are sufficient for navigation in public spaces, such as streets and parks, and even in indoor spaces, such as in airports, train stations, or shopping malls.

However, there was a large variability of achieved radii between subjects. Table 2 shows the mean directional changes and turning radii for each participants, ordered by decreasing effect size. For this table the medians of the trials for each condition and user were computed. Then for left and right the stimulus levels were chosen that worked best for that subject. Three groups of participants can be identified: The first six have rather small turning radii, the next five have medium turning radii that appear to be sufficient for coarse navigation, and the last three have very large turning radii, which would not be sufficient for successfully steering them.

Questionnaire

After the 40 walking trials we asked participants to fill in a questionnaire (5-point Likert scale, 1=strongly disagree, 5=strongly agree). All participants strongly agreed that they got used to the stimulation after a few walking trials with a median *(M)* of 5 and median absolute deviation *(MAD)* of 0. Furthermore, we were interested in the quality of the stimulation signal. We received mostly neutral responses for the question whether the signal was palpable during actuation (M=3, *MAD*=1). Users agreed that they could differentiate the 3 different strengths on both legs (M=4, *MAD*=0). All participants described that they could clearly feel the EMS signal. However, 9 participants said that they would use such a system in everyday life for pedestrian navigation. They did not fear running into an obstacle when wearing the eye mask during the trials (M=1, *MAD*=0). Finally, they did not find actuation to have a negative impact on balance (M=1, *MAD*=0).

Qualitative Results

During the experiment we observed two major challenges. First, we found that holding the leg in a relaxed manner during calibration was crucial for achieving the desired effect. Second, the placements of the electrodes required high precision. If electrodes were placed too far off the muscle ($>$0.5 cm), either no actuation was possible or other muscles, such as the musculus quadriceps femoris were actuated, which led to the leg being fixed in its position.

PEDESTRIAN NAVIGATION STUDY

Having acquired an understanding of the fundamentals of EMS-based control of walking direction in the lab, we performed a study to gain insight in how well the approach works in a real environment. We invited 4 male participants (*mean*=25.3, *SD*=1.3). Three of them are right-footed and do sports 8 to 20 times a month. All use phone-based navigation systems up to 5 times a week. To observe participants in context and be able to flexibly react to the environment we opted for a Wizard-of-Oz study in which the experimenter followed the participant and manually triggered actuation signals. The study was video-captured for post-hoc analysis. Participants were equipped with the EMS prototype.

Study Design

The study took part in a park (appr. 380 $\times$ 400 m) with many paths and meadows. This allowed the study to be conducted in a safe environment, which at the same time provided a multitude of different paths. We defined two different routes. Note, that participants were unaware of these routes

Figure 8. Routes for outdoor study (left turns marked red, right turns marked green): Route 1 on existing trails with a length of 991 m (left) and route 2 across country with a length of 552 m.

- Route 1 had a length of 991 m and included 7 right turns and 9 left turns. The route followed existing trails and took participants about 12 minutes to complete (Figure 8, left).
- Route 2 was 552 m long and ran mainly across lawn. Since there were no marked trails we defined landmarks that users needed to pass. The route included 8 left and 4 right turns and took participants on average about 7 minutes to complete (Figure 8, right).

Apparatus and Procedure

As participants arrived at the lab, we described the study and had them fill in a demographic questionnaire and a consent form. We calibrated the EMS system using the same procedure as described above, before walking over to the park. Participants were asked to walk casually and to just let the turns happen, as triggered by the actuation. Furthermore, we asked them to pay attention to any obstacles, potholes, and bumps – particularly when walking on lawn, and to stop or circumvent these as necessary. We then began with the walk. The experimenter followed the participant and triggered actuation at turning points, using the navigation app described earlier. After the participants completed both routes, we conducted a semi-structured interview, which we audio recorded.

Results

We recorded 88 minutes of navigation videos and 30 minutes of audio interviews. In the following we report on findings from observations and interviews made during the study. From our data we identified five categories, in which we grouped our findings, namely general experience, steering and direction changing, comparison to other navigation systems, mental load, and ethical concerns.

General Experience

Overall feedback on the navigation system was very positive. All participants stated that they were quite surprised by the *"very good performance of the system, particularly for narrow curves"* (P2). Asked about their experience and thoughts in the beginning of the test, some participants were concerned of giving away control to the navigation system. For example, P0 reported that at first he was *"afraid of running into obstacles when not changing direction in time."* P0 reported a situation on a small bridge where he was *"afraid of walking into a man sitting on the floor there."* However, the experimenter guided him smoothly around the man, making the participant feel *"much more relaxed in the following."* We explored in which situations the navigation system works best.

P1 stated that the system worked best in situations where he *"walked in a relaxed manner."* Furthermore, the ground texture seemed to have a strong influence. Participants reported that even ground (e.g., pavement) worked significantly better than bumpy ground or walking in high grass.

Steering and Direction Changing
P0 said *"I was walked in the [right] direction."* P2 reported that *"only the actuation and not the tactile feedback changes the direction."* Similarly, P3 estimated that 90% of the direction changing came from the actuation and *"maybe 10% from feeling [the signal]."* Participants also found it *"interesting not to know in which direction the system was guiding me next."* P3 stated that *"changes in direction happened subconsciously."* P0 said that he was thankful that the experimenter steered him around the puddles and people.

Furthermore, we wanted to learn about the degree to which people could still control their walk while using our system. Here, participants stated that they could always change the direction themselves and stop at any time.

Comparison to Other Navigation Systems
All participants could imagine to use the system in practice. They felt the system to be best applicable for walking and jogging. Moreover, participants were not concerned of using such a system in traffic. Asked about the differences to commercially available navigation systems, participants particularly liked the fact that they were not provided visual feedback, thus, *"freeing capacities"* (P1). P3 particularly liked that he could focus more on the environment compared to traditional navigation systems.

Mental Load
Participants stated that while in the beginning they were consciously aware of the feedback, they *"did not think about it anymore after just a few minutes"* (P1, P2). In general, participants reported the navigation to be very subtle so that they could easily focus on their surroundings. An interesting comment was provided by P0 who stated to *"concentrate less on the close environment after some time."* In a similar manner, P2 stated to not solely focus anymore on the direction he was walking into. In contrast he found the system *"particularly useful in situations where [he] wanted to use his smartphone."* He would even try out reading some text during the test, using the system like an autopilot. Afterwards he stated that only *"one still has a bit of an eye for the surroundings [...] enough for orientation."* These findings suggest that an emphasis needs to be put on designing the system in a way such that it reliably detects potentially dangerous situations and warns the user, for example, through a secondary feedback channel.

Concerns
Finally we were interested whether users had any concerns of being controlled by an application. Surprisingly, none of the participants came up with such concerns. All of them felt that being controlled was ok, since they could at anytime take over control and 'override' the system. P1 compared the system to the *"cruise control in the car,"* where users could regain control at anytime.

DISCUSSION

Application Scenarios
Delivering actuation signals for pedestrian navigation has a wide range of applications. It is particularly useful if the user is cognitively engaged with other tasks, needs to receive precise information privately, or if multiple users need to be spatially coordinated to reach some goal.

In sports, for example, actuated navigation may steer long-distance runners via different jogging trails on different days for increased variety and enjoyment, or to choose the optimum path to reach a particular training goal. In team sports, actuated navigation may coordinate the orchestration of team actions. New variants of team sports may be devised in which the coach or an external player may influence the moves of the team. Coordinated action is also relevant for firefighters, who may be steered through a building towards the relevant spot. Coordination of larger crowds is also conceivable. Imagine visitors of a large sports stadium or theater being guided to their place, or being evacuated from the stadium in the most efficient way in the case of an emergency. Actuated navigation may help disoriented elderly people to find their way home. Actuated navigation may be part of tourist and city guides to allow visitors to focus on the sights rather than on the navigation task as the walk through the city. Finally, it may facilitate serendipitous encounters in public places. In all these examples, actuated navigation is unobtrusive, private, and may be overridden if desired.

Limitations
We use EMS to implement actuated navigation. Although EMS (in the form of functional electrical stimulation) has been used for some time in rehabilitation, its use in the general public is not yet widespread. However, EMS is gaining popularity as a fitness training method. Current EMS systems are still somewhat inconvenient, in particular regarding the placement of the electrodes. In our experiments we found that an exact placement of the electrodes is needed. There are individual physiological differences and small placement differences can deteriorate the intended muscle stimulation. We used simple single-pad surface electrodes. In rehabilitation, multi-pad electrodes have already successfully been deployed. Via machine learning techniques, the optimal activation of a subset of the pads can achieve optimal control of the intended muscle. It may be possible to integrate future multi-pad electrodes in underwear, obviating the need for separate placement of surface electrodes.

The lab experiment showed that open-loop control is not sufficient to achieve a precise angular change of the walking direction, as this depends on many parameters, like the weight of the user, the resistance and impedance of the skin, and the state of the muscle. Systems that aim to enable precise control, even of a single muscle, require closed-loop systems with sensors that feed back the state of the limbs and joints. However, for actuated navigation it is sufficient to set an acceptable level of muscle stimulation and control the amount of change via the duration of muscle stimulation.

We found that for a small percentage of our test users EMS had very little or no effect on walking direction. Given the data that we have, we can only speculate whether this was due to sensor placement, higher skin resistance, physiological differences in muscle position, or unconscious counteracting against the small directional force generated by EMS. These questions have to be investigated further in future work.

CONCLUSION

With our research we layed the foundation for future navigation systems that aim to reduce the users' mental load. Opposed to prior approaches we focus on user actuation rather than conveying navigation information. We provide a proof of concept implementation, showing the feasibility of our approach. In an initial lab study, we showed that EMS actuation can change users' walking direction. In a subsequent field study we successfully "cruise controlled" pedestrians along two routes across a public park. Feedback from the study participants suggests that the approach works reliably and that the modification of the direction came mostly from the actuation rather than from the user's succession of the tactile stimulus. From a safety perspective it is particularly important that the participants could easily "override" the actuation, which may be important as obstacles appear along the trajectory of the user. Furthermore, participants had no concerns with regard to being controlled by the system.

In the future we plan to include a feedback loop for outdoor navigation (e.g., through GPS positioning) to automatically navigate the user towards a target destination. This will allow the system to be tested in a real-life setting.

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