TickleFoot: Design, Development and Evaluation of a Novel Foot-Tickling Mechanism That Can Evoke Laughter

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Tickling is a type of sensation that is associated with laughter, smiling, or other similar reactions. Psychology research has shown that tickling and laughter can significantly relieve stress. Although several tickling artifacts have been suggested in prior work, limited knowledge is available if those artifacts could evoke laughter. In this article, we aim at filling this gap by designing and developing a novel foot-tickling mechanism that can evoke laughter. We first developed an actuator that can create tickling sensations along the sole of the foot utilising magnet-driven brushes. Then, we conducted two studies to identify the most ticklish locations of the foot's sole and stimulation patterns that can evoke laughter. In a follow-up study with a new set of participants, we confirmed that the identified stimuli could evoke laughter. From the participants' feedback, we derived several applications that such a simulation could be useful. Finally, we embedded our actuators into a flexible insole, demonstrating the potential of a wearable tickling insole.

CCS Concepts: • **Human-centered computing** → **Haptic devices**; *Empirical studies in HCI;*

Additional Key Words and Phrases: Tickling, haptics, elciting emotions, eliciting laughter, magnetic locomotion, fun, laughter

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1 INTRODUCTION

Human touch is a powerful tool for interpersonal communication, as it generates both physical and emotional responses. Among the various forms of touch, a tickling sensation can arise when the body perceives a foreign stimulation. For tickling, humans show a variety of reactions, such as laughter, smiling, twitching, and even goose bumps [18, 54, 66]. Tickling elicited by a slight touch is

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considered as knismesis, which creates an itching sensation [67] but does not evoke laughter [33]. In contrast, gargalesis evokes laughter [33], a form of tickling resulting from heavy touching of specific body locations [18, 54] which involves an integration of multiple mechanoreceptors and nociceptors signals [30, 64, 83]. Prior research in psychology has shown that tickling which evokes laughter could be a great stress reliever if used as a positive social interaction [24, 33, 82]. Also, tickling among loved ones such as friends, family, and lovers is considered as a source of communication to show affection [66]. As such, we believe a tickling artifact that evokes laughter could open up applications related to remote interpersonal, playful interactions, and entertainment.

According to literature, gargalesis tickling needs an element of unpredictability or uncontrollability [78]. Hence, self-tickling that evokes laughter is impossible as our brain's cerebellum can predict a self-tickle and alert the brain's anterior cingulated cortex to attenuate the tickling sensation [7, 8, 14, 15, 39]. Although tickling is interpersonal, requiring another person as a source of touch [18, 45], Harris and Christenfeld [36] demonstrated that a machine could cause ticklish laughter. Previous research has proposed different artifacts that can provide tickling stimulation. In creating such a sensation, these artifacts were mainly applied at the following body positions: wrist [47], ribs [76], cheek [60], hand [27], or arm [67]. To our knowledge, a prior work named Phantom Slipper can be considered as the first and only wearable artifact which deployed tickling at the foot [48]. This work primarily focused on using two vibration motors to convey vibrotactile information about the objects moving around the feet in a virtual environment. A relatively recent work explored the interaction between audio and tickling stimulations to elicit mirthful responses [26]. The authors used a vibration actuator attached to a lever to study the relationship between perceived ticklishness and vibration. However, limited knowledge is available if those artifacts could evoke laughter.

The most ticklish parts of the human body that evoke laughter are areas that are not usually touched by others [18, 54], such as the soles of the feet and armpits. Among these locations, the feet are extremely interesting as the sole has a large concentration of highly sensitive free nerve receptors, mechanoreceptors, nociceptors, and Meissner's corpuscle from both locations. Moreover, these receptors are located closer to the hairless skin surface at the sole of the foot, making this area notably more ticklish than others [2, 25, 46]. Inspired by the work of Fortin et al. [26], we aim at designing and developing a novel foot-tickling mechanism that can evoke laughter in this article (See Figure 1). Using the magnetic locomotion principle [9], we developed a tickling actuator, a brush attached to a moving magnet that creates a tickling sensation when in touch with the foot. We then conducted two users study to identify the most ticklish locations and stimulation patterns that could evoke laughter. We conducted a follow-up study with different users to verify that our design could successfully elicit laughter. From the participants' feedback, we derived several application scenarios that our stimulation could be considered useful, such as connecting with loved ones for playful interactions. Finally, we embedded our tickling actuators into an insole and tested it with several participants. In summary, the main contributions of our work are twofold:

— An artifact contribution where we designed a modular actuation mechanism that can be integrated into an insole to create tickling sensations and evoke laughter.
— An empirical contribution where we conducted user studies to find the most ticklish locations of the foot, stimulation patterns, and verification that our system can evoke laughter.

2 RELATED WORK

2.1 Affective Interfaces

In literature, many interfaces aim at recreating human touch, mainly for mediated affective communication. Such works use various haptic actuators, which provide a variety of sensations for

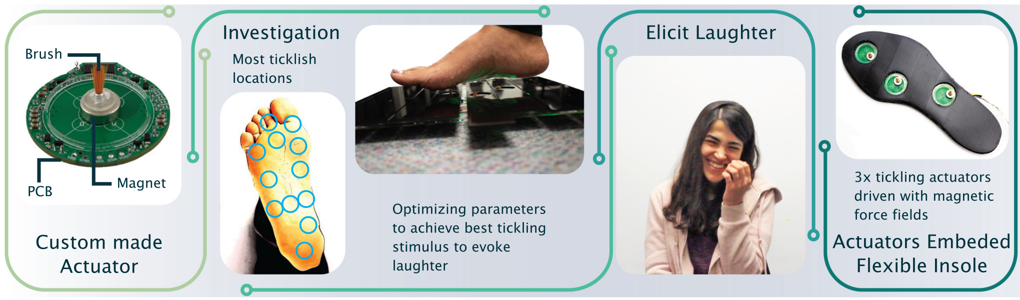

Fig. 1. Our starting point was the exploration of the most ticklish locations the foot offers using a custom made actuator that we designed based on magnet force fields. The movable part is a tiny brush mounted on a magnet that tickles the sole of the foot. After identifying most ticklish locations, we investigated the optimal setup for our tickling actuator to achieve the best tickling stimulus. Finally, the actuators were embedded into a flexible insole.

different body locations. Vibration motors [22, 43, 61, 77], voice coils [17], linear resonant actuators [80], **shape memory alloys (SMA)** [56, 57], pneumatic actuators [81], air flows [49, 74], magnetic cosmetics [9], and brushes attached to DC motors [59, 72] are some of the actuators found in literature for touch recreations. These interfaces exist in various form factors to provide touch sensations to different body locations, such as the hand [62, 73], wrist [42], chest [55, 76] abdomen [75, 76], feet [20, 21, 48, 52, 53], and arm [56]. In terms of the sensation recreated, skin dragging [4, 29, 42, 71], stroking [47], tapping [17, 51], squeezing [5, 19, 70], and pinching [56, 57] are some of the touch gestures that have been recreated in previous works. In addition to touch, only a few interfaces have been developed to recreate a tickling sensation. Since our interest concerns tickling, the following subsections will elaborate on the physiology behind tickling and tickling artifacts found in literature.

2.2 Tickling

2.2.1 Stimulus Triggers and Tickling Interfaces. Although a number of artifacts deploy a variety of feedback modalities to trigger affective interactions [1, 41], only a few artifacts aimed at tickling users. Many of those have already been reviewed by Fortin et al. [26] in 2017. Below, we cover the work before 2017 as well as tickling artifacts presented after 2017 that are relevant to the discussion. We break down the discussion under different stimulus triggers that can cause a tickling sensation. Under each section, we also discuss if any digital tickling interface used particular stimulus triggers.

Vibration: A vibrotactile stimulus can feel like a massage on the skin, depending on the force, frequency, and body area being stimulated. Although vibrations at the foot sole may provide disturbance for some users [20, 21], literature has shown that it can be a useful tickling tool [26, 27, 48]. As also identified in prior research [26], most tickling artifacts are based on vibrations or laterotactile stimulation, aimed at tickling different body locations. For instance, “CheekTouch” is a smartphone casing equipped with touch sensors and vibration motors which can create a tickling and stroking sensation on the cheek while having a conversation [60]. “Kusuguri” is a similar example, which creates bidirectional hand tickling while using a mobile phone. It uses additional visual feedback on the screen to increase the perceived tickling sensation by showing a finger touching the user’s hand [27]. Although the approach of providing additional visual feedback looks promising, the synchronisation of visual and vibrotactile feedback to evoke a ticklish sensation was mainly found to be challenging. In addition to tickling interfaces based on the vibration of mobile devices, previous work has also explored a few wearable tickling interfaces. A prior work named “Phantom

Slipper" is the first artifact claimed as a tickling interface, which assumed the form of a foot-worn tickling apparatus [48]. In a preliminary user testing, the artefact utilised two vibration motors to generate a tickling sensation. In 2010, Dzmitry et al. [76] introduced a collection of affective interfaces for remote affective communication. In this work, authors introduced a tickling interface, "HaptiTickler", an artefact with four vibration motors to tickle each side of the body's rib cage. These four vibration motors were used to render spatio-temporal vibration patterns to create a tickling similar to a human finger's movements [76].

Feathers: Century-old literature has told us many stories about using feathers to create an unstoppable tickling sensation. For instance, applying goose feathers to the sole of the foot was used as an effective tickling technique, even in recent history [37]. Another recent work aimed at studying physiological responses to affective tele-touch implemented an arm-worn tickler based on a feather mounted on a DC motor [12]. The motor can be rotated in five increasing levels of speed. However, not many details were included in the relationship between rotation speed vs. triggered tickling.

Blunt Objects: Small, blunt, and rod-like objects such as back-scratchers, hairbrushes, combs, q-tips, and pencils can create tickling sensations. These objects work best for lower-body tickling, especially on soles of the foot [30]. In digital tickling interfaces, blunt objects were used to provide tickling sensations using laterotactile stimulations on the skin. For example, the artifact named "The Tickler" is a wrist-worn tickling device, which uses SMA to move an array of parallel bars laterally over the skin [47]. This type of actuation is much slower and softer compared to a sensation provided by a motor. Light stimulation and the silent actuation is the main advantage of the SMA-based actuation. However, light touching of the wrist may not provide gargalesis tickling [33]. Another work called "Ant in the Pants" is an arm-worn sleeve embedded with an array of motors mounted on blunt nylon fibers [67]. The artifact recreated the sensation of ants crawling up the wearer's arm. Hence, one can argue that this artifact mainly creates knismesis rather than gargalesis [33]. The artifact was used with a table-mounted monitor, with which participants were able to see ants crawling up their hand and arm. It was primarily used to enhance the immersive experience in virtual reality by providing tickling-like sensations.

Pinwheels: The so-called Wartenberg wheel[1] has small rods arranged circularly and are made of stainless steel. These are small handheld rods with the spinning wheel at the tip that can be rolled over the skin to test the nerve cells' functionality, which Robert Wartenberg invented in the 19th century. When rolled gently back and forth over the skin, these can cause an odd, discomforting ticklish sensation [58] similar to knismesis.

EMS: Many HCI researchers have described EMS as providing light to strong tickling sensation depending on the type of voltage and strength of the current floating from the electrode through the muscle [31, 51, 68]. Although EMS has not yet been used to invoke tickling purposely, it has great potential. However, we believe that the side effects on health, such as phantom sensations after stimulation, must be explored before using this technology to evoke tickling.

Brushes: When it comes to creating tickling, previous research has demonstrated that brushes work similarly well as feathers [63]. Moreover, brushes are widely available, inexpensive, exist in several degrees of hardness, and can be easily integrated. Therefore, we selected brushes for our actuator.

Many of the digital tickling artifacts mentioned above are not rigorously evaluated to understand whether they could elicit a tickling sensation that evokes laughter. Moreover, some of the tickling artifacts were subsystems of a larger system developed for affective communication [76]. So far, only one recent study has evaluated the relationship between vibration frequency and

[1] https://en.wikipedia.org/wiki/Wartenberg_wheel.

perceived ticklishness [26]. These researchers used a custom-made stationary tickling interface, which tickles the sole of the foot by using a single end effector driven by a vibration actuator. According to the authors, a single point actuator could not effectively evoke tickling that creates laughter reactions. We believe that creating tickling sensations aiming to generate laughter is not entirely explored yet.

2.2.2 Psychology of Ticklish Laughter. According to Harris and Christine, the psychology of tickling that evokes laughter has a double-edged nature [34]. On one hand, getting tickled by a stranger is unpleasant and awkward [34, 66, 79]. Although a person's external response to tickling looks similar to laughter and enjoyment, many adults have reported not liking being tickled [34]. On the other, some people find tickling pleasant and actively seek it. Also, many are convinced that others enjoy being tickled. Moreover, some work suggests that tickling is more pleasant and enjoyable when it is consensual and between people with positive social relationships [66]. For example, children seem to have fun when parents, siblings, or friends tickle them. A survey also indicated that people are most likely to get tickled by friends, family, and lovers [65]. Furthermore, playful tickling between a couple is considered a source of communication that could strengthen affection between each other. Research also shows that consensual tickling may release stress and can be used to prepare for tense situations [24]. For example, tickling a child before getting an injection may reduce anxiety.

3 TICKLEFOOT

3.1 Design Rationale

The main goal of our research is to create tickling sensations that evoke laughter. Therefore, it is important to stimulate the most ticklish body location, such as the sole of the foot [18, 54], in a way that feels similar to an interpersonal tickling action. The glaborous skin of the sole already contains many nerve endings related to touch, pressure, pain, and vibration. Prior work has mapped the distribution of those receptors of the sole of the foot [2, 46]. To evoke laughter, we needed to stimulate multiple areas at once to generate a gargalesis tickling reaction. Moreover, inspired by the vision of assistive augmentation [40], our long-term goal is to provide a realistic tickling sensation in a wearable form factor which may open up many unexplored applications. Hence, the actuator should not interfere with the user's comfort. The interface—including the actuation mechanism—should be of a thin form factor. The device should also preserve some flexibility to retain normal walking and prevent impacts on the user's gait. Regarding the durability aspect, new mechanisms should be used rather than relying on mechanical motors, given they are prone to break when force is exerted. Actuators, such as vibration motors, can be found in small form factors; however, their lateral movement is limited, which may not simulate the best tickling sensation. At the same time, developing a thin form factor with brush-mounted DC motors and linear actuators is difficult, especially when using multiple actuators. Recent work has explored an actuation mechanism based on magnetic locomotion [9]. We further developed this actuation principle to integrate it into a flexible and thin insole. After identifying the tickling body location and the actuation mechanism based on prior research, two studies were conducted to identify the most ticklish locations of the foot to determine the actuators' placement and actuation parameters, such as movement patterns and frequency that creates tickling to evoke laughter.

3.2 Tickling Actuator

3.2.1 Hardware Implementation. To generate a garglesis tickling, we would need to move the brush in a certain area. Recent research has shown the durability of a locomotion technique that relies on magnets rather than motors [9, 13]. Therefore, we further developed a modular actuator

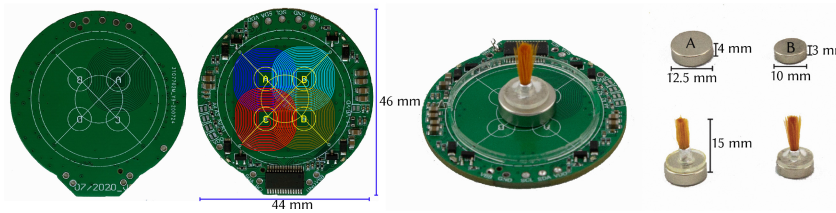

Fig. 2. The PCB module, which generates a combination of electromagnetic fields by using four coils named A, B, C, and D. An actuator consists of a PCB module, a magnet, and a brush. The pull force of magnet A is 3.68 kg, while the pull force of magnet B is 2.0 kg.

mechanism capable of actuating multiple brushes simultaneously while keeping a low profile. The brushes are mounted on permanent magnets that stimulate the skin.

In this section, we provide details on the development and implementation of these actuators. Each actuator consists of three main components: A PCB board, which generates a combination of electromagnetic fields, a neodymium permanent magnet, and a brush which is mounted on the magnet.

PCB module: The PCB design consists of four coil actuators (see Figure 2). The coils generate a small magnetic field, which attracts the permanent magnet. The magnetic field of the coils can be approximated as a cone [50]. The size of each coil is 15 mm × 15 mm, 15 turns, and 1.85 Ω. The module is powered by a High-Drain 3.7V Lithium-ion battery (18650), with a maximum discharge rate of 20A. With this setup, the maximum current that a coil can drain is 1.8A. Each of the coils is placed at a different layer of the 4-layers PCB, with an overlap of 25%. Each of the coils is driven by a PWM signal and a MOSFET (N-MOS-AO3400). The current of the coil is proportional to the duty cycle of the PWM signal, and so the magnetic field that defines by $B = \mu nI$, where μ is the permeability of the core, n the coil turn density, and I the current. Finally, the module integrates an I2c 16-channel 40 KHz PWM generator (PCA9635), which is controlled by a "Microcontroller Board", a Teensy 3.6.

Neodymium permanent magnet: We selected the N45 neodymium permanent magnet (from now onwards, denoted as magnet). The selection needs to be done carefully as it has a major effect on overall system performance and the overall thickness of the wearable form factor of the insole. The bigger the size of the magnet, the higher the magnetic field. This increases the momentum of the brush stroke, which may provide stronger stimulation. However, the weight and the surface area of the magnet increases the surface friction which may reduce the momentum, resulting in a reduced stimulation strength. Also, the shape of the magnet is highly important for a wearable form factor. We tested a range of disc-shaped magnets with our PCB module. Considering the size, weight, stability of the motion, and the pull force, we decided to conduct our studies with two magnets. The selected magnets are shown in Figure 2. The pull force of magnet A is 3.68 Kg while the pull force of magnet B is 2.0 Kgs. The meaning of the pull force is the force required to prise a magnet away from a flat steel surface when the magnet and metal have a full and direct surface-to-surface contact. A higher pull force means a higher magnetic field which can generate a higher force. A higher force may have an impact on ticklish sensation.

Brush: The brushes are made of size number 2 round paint brushes that consist of imitation golden sable hair. The type of the brush selected was based on some pilot experiments testing a variety of round brush types with two different sizes (2, 4), and two different material (golden sable hair, nylon). In the pilot experiments, we stimulated participants feet using each brush and asked

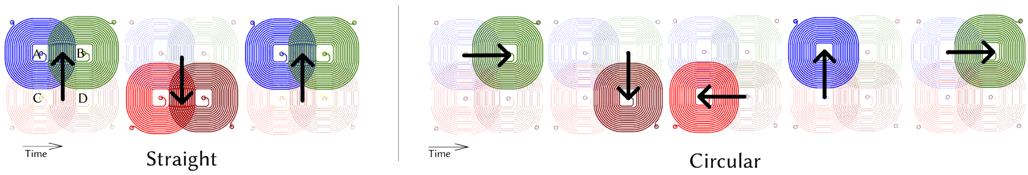

Fig. 3. Actuation sequence of a cycle of the two actuation types in a time series. One cycle is a complete "straight" or "circular" trajectory of the magnet.

them to select the brush that tickled them the most. All participants selected the brush made from golden sable hair, as it was more ticklish than nylon brushes. Nylon brushes created discomfort due to their hard bristles compared to golden sable hair. From the two sizes, we selected number 2 as it can firmly fix on acrylic without losing the bristle density compared to size 4. The brush was mounted to the magnets as shown in Figure 2. The average height of a brush including the magnet is ~15 mm. However, for the arch area of the foot, we used a slightly longer brush with an average height of 40 mm, which allows us to stimulate a normal human foot arch with an average arch height [16].

3.3 Technical Parameters and Constraints

The PWM signals are used to control the brush mounted magnet. When a coil is activated, the magnet is attracted to that coil. Therefore, we added 4 coils to achieve 2 DoF motion. From the large number of patterns we can generate, we implement 2 main moving patterns: "straight" and "circular" as shown in Figure 3. To generate smooth transactions of the brush actuator from one coil to another, we progressively changed the PWM value from 0 (Low) to 255 (High). For example, on a movement from left to right, coil A PWM value will decrease from High to Low, while coil B PWM value will increase from Low to High. The overall speed of the magnet is defined by how fast each coil goes from one PWM value to another. In other words, how large is the increment or reduction of PWM value in a single step (A step is the size of PWM increment/decrement). The larger the step, the quicker the magnets movement. This speed will also affect the overall frequency that the magnet oscillates in between coils. When the frequency changes, the distance that magnets travel per cycle also changes, which changes the stroke length of the brush.

To analyse the behaviour of the magnet in different frequencies, we activate the coils in different PWM steps and measured the distance that the magnet moves in a single cycle (See Figure 3 for the definition of a cycle in each pattern). The cycle frequency (Hz) or the number of completed "straight" or "circular" trajectories per second is also measured. According to our observations, in "straight", the magnet moves nearly the same total distance (30 mm) up to 7 Hz. However, after around 7 Hz, the total moving distance decreases again. Therefore, when the oscillation frequency is high, the stroke length becomes lower.

In circular patterns, when the frequency is increasing, the distance also slightly increases. However, the increased frequency by increasing the PWM step, makes the magnets motions unstable and unpredictable. This is due to the high velocity when it moves from one magnetic field to another. Therefore, we stopped increasing the frequency at around 3 Hz to ensure stability and controllability of the magnet's movement.

3.4 Connecting Multiple Actuators

Controlling actuators can be done with any microcontroller which incorporates an I2C bus. In our studies, we used an Arduino Uno microcontroller board. For the later prototype, we used a Teensy 3.6 board. Multiple actuators can be serialized using 4 cables (power, Ground, 2 wire I2C bus). To address each actuator individually, a unique address has been hardwired to each actuator.

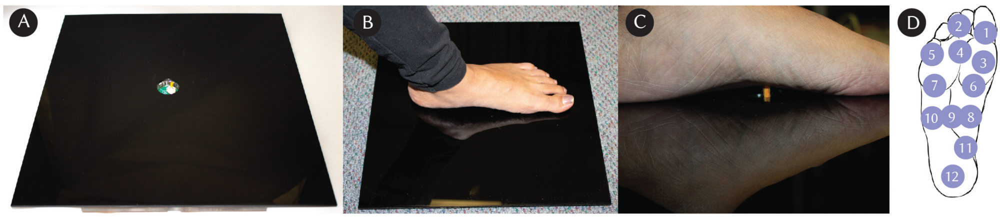

Fig. 4. (A) The testbed with a single actuator module. (B) & (C) Participant keeps their foot on top of the testbed to ensure the actuator's brush touches the sole. (D) Based on literature, we studied 12 locations of the sole of the foot.

Minimum Distance between Multiple Actuators: The minimum distance between multiple actuators depends on the minimum distance that two magnets can keep without being attracted or repelled to/from each other. When the magnets become more powerful, the minimum distance between two actuators increases. This distance for magnet A is 60 mm and 50 mm for magnet B.

3.5 Study 1: Identification of Ticklish Locations

Although the foot is considered one of the major body locations for tickling, different factors, such as gender, age, the frequency of wearing shoes, and skin thickness, impact the perception. Therefore, individual differences of perceived ticklishness of different foot locations may be present. Another constraint is the impossibility to tickle many locations at once without keeping a certain minimum distance. Therefore, we ran a study to identify the most ticklish areas of the foot to maximise the success of our final prototype. Although individual differences cannot be switched off, we aim at finding common locations.

3.5.1 Study Design.

Apparatus: We developed a testbed with a single actuator module, as shown in Figure 4. The testbed was built using several layers of acrylic, which covers and protects the electronics when participants keep their foot on top of it. Also, the acrylic is supported to distribute the weight and avoid applying direct pressure on the brush. The height of the platform was also adjusted so there is a minimal extra pressure exerted on the brush. This way, the brush can freely move with reduced friction. We used the two magnets selected previously, one with a size of 12.5 mm (magnet A) and the other one with a size of 10 mm (magnet B)—see Figure 2. Four brushes (two short and two long ones) were used, which were matched to the magnet's size and the location of the foot. Both long brushes were used for points located in the foot's arch region, as shown in Figure 4. The brush used in magnet A is slightly shorter than the one attached to magnet B. This was done to make sure that the effective length of the actuator is the same. The actuation power and the actuation pattern and frequency were kept constant throughout the study.

Participants: We recruited 13 participants (7 females) aged between 22 and 45 (M = 28.6, SD = 5.8). The inclusion criteria of our study participants required them to be healthy. Participants with any lower extremity disabilities or chronic illnesses, such as diabetes, were excluded since it may diminish the foot sensation.

Task and Procedures: Before filling consent forms, participants were informed that the study aims at identifying their foot's most ticklish locations by using a wearable tickling device. After collecting demographic data, we asked them to self-rate how ticklish their body might be. We used a 7-point Likert scale (1- *Not ticklish at all*, 4- *Ticklish*, 7-*Extremely ticklish*). Next, we asked

All Participants (n=13)	L9 M=4.3 SD=1.5	L4 M=4.2 SD=1.8	L8 M=4.2 SD=1.7	L6 M=4.1 SD=1.5	L10 M=3.9 SD=1.8	L2 M=3.8 SD=1.3	L7 M=3.7 SD=1.7	L11 M=3.7 SD=1.8	L1 M=3.6 SD=1.6	L5 M=3.5 SD=1.5	L3 M=3.2 SD=1.7	L12 M=2.4 SD=1.5
Females (n=7)	L9 M=5.3 SD=1.4	L4 M=4.8 SD=1.9	L10 M=4.5 SD=1.9	L11 M=4.5 SD=2.0	L8 M=4.4 SD=2.2	L7 M=4.2 SD=1.8	L6 M=4.2 SD=1.7	L2 M=4.1 SD=1.4	L1 M=3.7 SD=1.6	L5 M=3.6 SD=1.6	L3 M=3.4 SD=2.2	L12 M=2.8 SD=1.8
Males (n=6)	L6 M=4.0 SD=1.2	L8 M=3.9 SD=0.9	L4 M=3.5 SD=1.5	L2 M=3.4 SD=1.1	L1 M=3.4 SD=1.5	L5 M=3.3 SD=1.3	L9 M=3.2 SD=1.0	L7 M=3.1 SD=1.2	L10 M=3.0 SD=1.3	L3 M=3.0 SD=1.1	L11 M=2.8 SD=1.2	L12 M=2.0 SD=1.0

Fig. 5. Summary of the perceived ticklishness of each location. The locations not significantly different from each other are included in the same box. After considering the significantly high ticklishness and the viable distance between two actuators, we selected L9, L4, and L6 (green-shaded cells) as preferred locations to tickle.

them to sit on a comfortable office chair and to keep their bare left foot on top of the actuator to touch one of the foot's 12 locations, as shown in Figure 4. Before actuation, participants were shown the actuation point on a paper and asked to move their foot to ensure the actuation brush touches the correct position. After the experimenter validated the position, each location was actuated using two magnets in 2 directions (longitudinal and latitudinal). Hence, participants received four different stimuli in each location, resulting in 48 different stimuli. At the end of each stimulation, participants were asked to self-report their perceived ticklishness on a 7-point Likert scale. Also, $5s$–$10s$ pauses were allowed between the stimulation and self-reporting to ensure participants' reactions were uninterrupted by the self-report prompt. The order of stimulating locations was counter-balanced across all 13 participants to remove the effect of adapting to the stimulus. The study was conducted in a soundproof room to minimise distractions. The entire study lasted approximately one hour.

Data Gathering: Since the study was aimed to identify the most ticklish locations of the foot after each stimulation, we asked the participant to rate their perceived ticklishness using a 7-point Likert scale (1- *Not ticklish at all*, 4- *Ticklish* 7-*Extrmely ticklish*). Additionally, we collected the self-rated ticklishness on a 7-point Likert scale (1- *Not ticklish at all*, 4- *Ticklish* 7-*Extremely ticklish*) at the beginning of the study, as mentioned previously.

3.5.2 Data Analysis. The overall self-rated ticklishness of participants was M = 4.76 (SD = 1.53). However, if participants were divided according to gender, the mean value of self-rated ticklishness is higher for female participants (M = 5.57, SD = 1.27) compared to male participants (M = 3.83, SD = 1.33).

To identify a significant difference between both genders' self-rated ticklishness, we conducted a Wilcoxon rank-sum test. The results show that there is a significant difference ($Z = 1.68$, $p < .05$). Therefore, we analysed ticklishness across all the participants and also, considered gender.

A summary of the perceived ticklishness of each location is shown in the Figure 5. Overall, location L9 (Location x: Lx) has the highest mean perceived ticklishness, followed by L4, L8, L6, L10, and so on. A Kruskal Wallis test showed that there is a significant difference between locations ($X^2{}_{11} = 57.64$, $p < .05$, $\epsilon^2 = 0.076$). A post-hoc analysis was conducted by using a Dunn-test to understand pairs that have significant differences. According to the Dunn-test, we clustered locations into different groups so that locations that are not significantly different are in the same group. For example, according to Figure 5, L9, L4, L8, and L6 are not significantly different. However, for all participants, L9, L4, L8, L6 showed a significantly higher ticklishness compared to other groups. We used the **Benjamini and Hochberg** (**BH**) method as the P-value adjustment method for post-hoc analysis. Also, for all the other post-hoc tests that we reported in this article, we used BH as our P-value correction method since it reduces false positives and minimises false negatives [44].

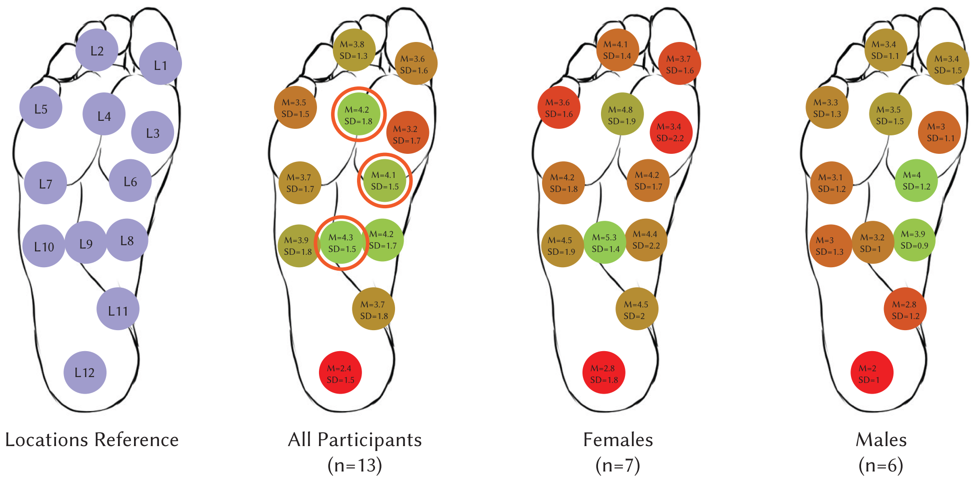

Fig. 6. The image visualises the summary of the mean perceived ticklishness of each location for all participants, males and females. According to the perceived ticklishness, the colour changes from green (the highest ticklishness) to red (the lowest ticklishness). The preferred locations for all participants are highlighted using red circles.

We also analysed whether the perceived ticklishness of each location is different by gender. As shown in Figure 5 for females, the highest ticklish location was L9, followed by L4, L10, L11, and so on. Also, a Kruskal Wallis test showed that there is a significant difference between locations ($X^2{}_{11}$ = 38.50, p < .05, ϵ^2 = 0.085). A Dunn-test grouped the locations that are not significantly different. It confirmed that L9 has a significantly higher ticklishness compared to other locations.

For males, the highest ticklish location was rated as position L6, while L8, L4, L2, and so on. ranked as the next highest ticklish locations. A Kruskal Wallis test confirmed significant differences between locations ($X^2{}_{11}$ = 42.94, p < .05, ϵ^2 = 0.12). A post-hoc analysis using a Dunn-test showed which pairs had significant differences. Then, we grouped the locations that do not having significantly different ticklishness. This analysis revealed L6 as the highest ticklishness for male participants.

3.5.3 Results. Following the summary (see Figures 5 and 6), and considering the known minimum distance that two magnets can exist together without getting attracted or repelled, we can finalise the three preferred locations as L9, L6, and L4. Although L8 also demonstrated promising results, in practice, tickling L8 requires a relatively long brush length for some users due to a well-pronounced arc region. Other users, however, demonstrate relatively flat feet, which requires a substantially shorter brush. Hence, position L8 may be unsuitable for a generalised tickling interface.

Next, we analysed whether the ticklishness of these locations (L9, L6, L4) depends on the direction and the pull force of the magnet. As each location was stimulated using two magnets (magnet A, B) in two directions (lateral:X, longitudinal:Y), we have four conditions to look at AX, AY, BX, and BY. A Kruskal Wallis test for all selected locations confirmed no significant difference between these conditions, which means that we can activate the brushes in any direction with any of the two magnets. The only constraint that should be controlled is the distance between two magnets to avoid attractions and repulsion. However, since the brush with magnet A has consistently shown a higher mean ticklishness, we selected magnet A as our preferred magnet for the next study and the final prototype.

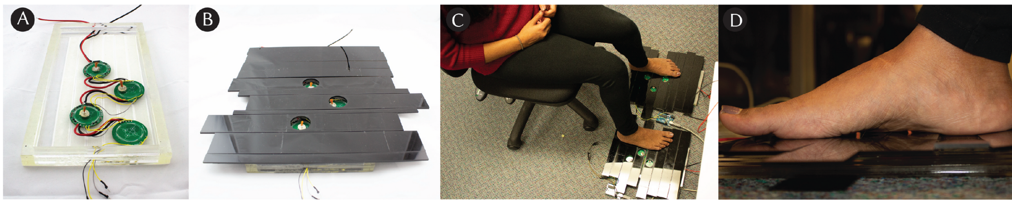

Fig. 7. (A) The base that carries the actuators. The distance between the actuators is adjustable. (B) After covering the base with rectangular-shaped acrylic plates, the testbed is completed. (C) Study setup where participant is waiting for the actuators to tickle their feet. (D) Closeup showing how actuators touch the sole stimulating the foot.

3.6 Study 2: Parameter Adjustment

The main goal of this study is to identify the most ticklish stimulus for our previously identified regions. For this, we vary the movement frequency of the two actuation patterns: "Straight" and "Circular" (See Figure 3). Also, we wanted to ensure that identified ticklish stimuli would provide a pleasant experience by evoking laughter but without surpassing the uncomfortable level. For this purpose, we adapted 5 point "behavioral scale" to analyze reactions of participants [35, 36]. Moreover, we also asked the participant to elaborate more on the emotions triggered.

3.6.1 *Study Design.*

Apparatus: As shown in the Figure 7, we developed an adjustable testbed. The testbed consists of two acrylic boxes. Velcro hook stripes were attached to the bottom of the box to attach four serialized actuators. This way, the distance between two modules is adjustable according to the participant's foot size. Also, the four modules were serialized in a way that adjacent modules have different magnetic polarities. This means adjacent magnets will be repelled from each other, which avoids magnetic sticking to each other once they accidentally get too close. Although we only needed three modules, we kept the extra module as a provision for an easier adjustment for different foot sizes. After adjusting the distance between modules, a temporary platform to place the foot was created using rectangular-shaped acrylic pieces, as shown in Figure 7. These pieces were fixed to the platform by using adhesive tape on the platform's edges. Three actuation modules were used to stimulate the foot according to the foot size of the participants from four serialized actuators. Brush heads were mounted on top of the selected magnet from the previous study. The entire session was video-taped to capture the participants' facial expressions and behaviour during our study.

Participants: We recruited 14 participants (8 females) aged between 22 and 45 (M = 28.6, SD = 5.8). Similar to the previous study, we selected healthy participants without any lower extremity disabilities or chronic illnesses.

Task and Procedures: After filling the consent forms, we collected the demographic data. The participants were then informed that three actuators would stimulate their feet in three locations (location 9, location 6, and location 4). These locations were visually represented by using the image shown in Figure 4(D). After sitting on an office chair, the participant was asked to hold their feet on the testbed platform to adjust the actuators to tickle the correct target locations. The adjustment took about 5 to 10 minutes. The adjustment was done and validated by the experimenter to ensure stimulation of the correct locations. Finally, the participant was asked to keep their feet on the adjusted platform. Next, an experimenter started providing the stimuli. There were two main patterns: straight and circular. Both stimuli were controlled in three frequencies. SF1: 3 Hz, SF2: 7 Hz, and SF3: 11 Hz for straight pattern covering low, medium, and high-frequency ranges.

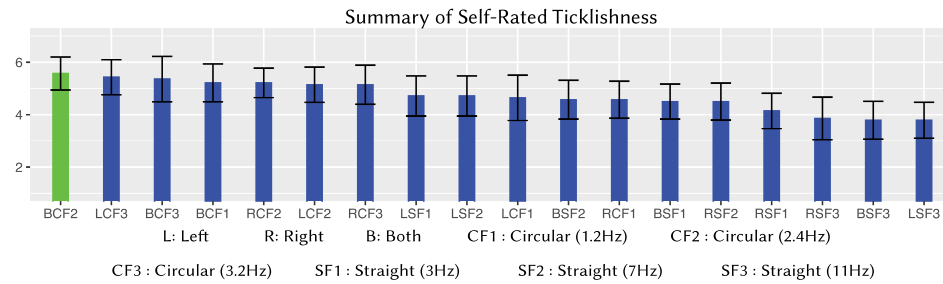

Fig. 8. Summary of each pattern's ticklishness. The highest ticklishness was rated by a "Circular" pattern with a frequency of 2.4 Hz (BCF2). The lowest ticklishness was rated by a "Straight" pattern with a frequency of 11 Hz. BCF2 (shaded in green) demonstrated a significantly higher ticklishness to all the other patterns. The error bars illustrates the 95% confidence interval.

For circular movement patterns, we selected three frequencies, which were: CF1: 1.2 Hz, CF2: 2.4 Hz, and CF3: 3.2 Hz. In summary, participants were given two patterns (straight, circular) × 3 frequencies × 3 feet conditions. The feet conditions included the stimuli conveyed to both feet together plus each foot individually. Altogether, participants received 18 stimulus conditions, as shown in Figure 8. All these conditions were randomised to minimise a possible adaptation effect. After each stimulus, participants were asked to rate their perceived ticklishness on a 7-point Lickert scale. Also, a $5s–10s$ pause was allowed between the stimulation and self-reporting to ensure participants' reactions were not interrupted by the self-report prompt. After self-reporting, another $15s$ pause was kept before the next stimulation. The study was conducted in a soundproof room to minimise distractions. The entire study lasted approximately 40 minutes.

Data Gathering: As per our previous study, after each stimulation, we asked the participant to rate their perceived ticklishness by answering the question "How ticklish was the last stimulus" on a 7-point Likert scale (1- *Not ticklish at all*, 4- *Ticklish* 7-*Extremely ticklish*). Finally, we asked the participant to describe what they felt during different conditions. For example, when the participant rated a specific stimulus as highly ticklish, we asked them to elaborate on the difference to previous stimuli that was rated lower. In post-processing, the video recordings were analysed and rated on a 5-point "behavioural scale" (0- *No apparent response*, 1- *Voiceless smile*, 2- *Laughter*, 3- *Laughter, twisting, and wiggling in response to the stimulus*, 4- *laughter and subject pulls limb away from tickling device*). We adapted such a scale from previous [35, 36] work to analyse reactions for tickling such as laughter. Moreover, this helped us to identify ticklish sensations that may go beyond the comfortable level. 3- *Laughter, twisting, and wiggling in response to the stimulus* and 4- *laughter and subject pulls limb away from tickling device* mainly considered as reactions for uncomfortable ticklish sensations.

3.6.2 Data Analysis. As shown in Figure 8, the highest mean ticklishness M = 5.57 (SD = 1.08) was rated by the F2: 2.4 Hz circular pattern when provided to both feet (BCF2). The lowest ticklishness was rated by the highest frequency (11 Hz) of straight pattern for the left foot and right foot (LSF3 and RSF3). A Kruskal Wallis test confirmed that there is a significant difference between ticklishness of the patterns with a moderate effect size ($X^2{}_{17} = 40.01$, $p < .05$, $\epsilon^2 = 0.098$). A post-hoc analysis by a Dunn-test confirmed that the rated ticklishness of BCF2 is significantly higher than all the other stimuli. Also, it confirmed that patterns LSF3, BSF3, and RSF3 have a significantly lower ticklishness than all the other stimuli. Furthermore, all the other stimuli except for BCF2, RSF3, BSF3, and LSF3 have been rated as significantly lower ticklish than BCF2 and significantly higher ticklish than LSF3, BSF3, and RSF3. The summary score of the 5-point behaviour scale

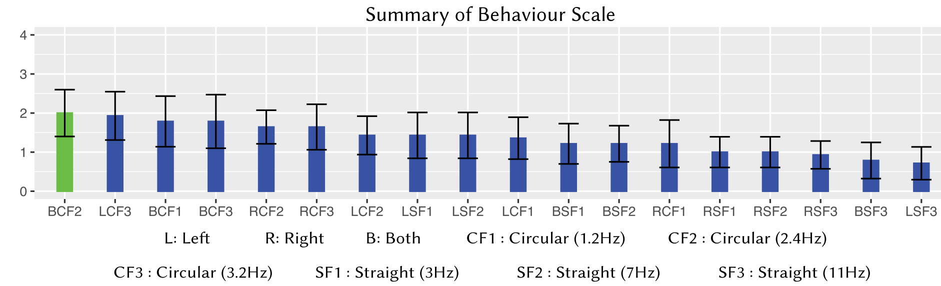

Fig. 9. The summary score of the behavioural score. The highest behavioural score was reported for pattern BCF2 (shaded in green). In contrast, the lowest behavioural score was reported for pattern LSF3. BCF2 (shaded in green) demonstrated a significantly higher behaviour score to all the other patterns. The error bars illustrates the 95% confidence interval.

(0- *No apparent response*, 1- *Voiceless smile*, 2- *Laughter*, 3- *Twisting and wiggling in response to the stimulus*, 4- *subjects pulls limb away from tickling device*) also shows similar results. According to the Figure 9, the highest mean score was reported as $M = 2$ ($SD = 1.03$) for circular patterns with a frequency of 2.4 Hz when provided for both feet (BCF2). This means that BCF2 can be considered as a usable tickling stimulation, which creates laughter without going beyond the uncomfortable level for the majority of participants. The high standard deviation is due to two participants demonstrating laughter while pulling the limb away from the tickling device. The lowest behavioural score was reported with $M = 0.71$ ($SD = 0.72$) for high frequency straight pattern LSF3. A Kruskal Wallis test also confirmed that there is a significant difference between behaviour scale with a moderate effect size ($X^2{}_{17} = 38.678$, $p < .05$, $\epsilon^2 = 0.093$). A Dunn-test confirms that the behaviour scale rated by BCF2 is significantly higher compared to all the other stimuli. Also, it confirmed that the stimuli LSF3 rated a significantly lower behaviour score than all the other stimuli. The stimuli BSF3 was rated significantly higher than LSF3 while rated significantly lower than other stimuli. Furthermore, the stimuli LCF3 was rated a significantly lower behaviour score than BCF2, while it was rated significantly higher than other stimuli.

3.6.3 Results. Overall, circular patterns had shown a generally higher ticklishness. As identified earlier, from these circular patterns, BCF2 even demonstrated a significantly higher ticklishness ($p < .05$). This could be due to the stroke length per cycle, which is higher in a circular stimulation. Also, the change of direction may have contributed to a higher tickling sensation. In longitudinal stimulation, when the frequency is high, the ticklishness significantly dropped. This could be due to the limited stroke length of the actuator in high frequency.

Also, we clustered what participants felt during different actuation. According to all participants, the highest-rated ticklishness (5, 6, 7 on a 7-point Likert scale) was related as "fun" and "joyful" sensations, which made them smile or laugh. The following quotes have been elicited; P11: "*When the tickling sensation is at the highest point, I found it more playful, and it made me laugh. I felt it like someone else is tickling my foot*", P9 :"*felt a pleasant sensation for what I felt at level 5 and 6. overall, it was a joyful session*", P2 :"*when I rated 5, I felt the most ticklish. It was a funny feeling which made me smile*". All these reactions are similar to a reaction in gargalesis tickling, which would make a person smile and laugh. The stimuli participants rated the lowest (1, 2 in a 7-point Likert scale) mostly provided a slight vibration or tapping feedback, which is somewhat similar to massaging feedback. P7: "*...The low scores I gave were for less ticklish stimulations because it felt more like a vibration ...*" P11: "*...when the brush was moving super fast in one direction, I felt like a brush was tapping my foot, it felt somewhat weird, but I didn't feel tickled...*"

3.7 Study 3: Investigation of Emotional Responses

Finally, we conducted a study to confirm that our informed parameters (tickling location and patterns) could create a fun and enjoyable tickling sensation which evokes laughter. Also, from the participants feedback and comments, we derived several example applications where TickleFoot could be useful.

3.7.1 Study Design. For the study, we recruited 12 healthy participants (6 Females) aged between 25 and 36 (M = 28.8; SD = 2.8) who did not participate in previous studies. We used a similar testbed that we used in the study 2. Additionally, we asked the participant to wear the Empatica E4 wristband to collect **skin conductance** (**SC**) data.

Task and Procedures: After collecting the demographic data and filling out the consent form, the participant was told that we would generate some stimulation at the sole of both feet, which they would later describe. After answering any questions that participants had, we started adjusting the testbed according to the participant's foot size—similar to the study 2. Additionally, we asked them to wear the Empatica E4 wristband on their left hand to collect data on SC. Before providing the stimulation, the participant was asked to close their eyes for one minute to record a baseline of their current SC. Finally, we asked the participant to keep both feet on the testbed, as we stimulated both feet three times. Each stimulus lasted for 10 seconds. There was a 5–15 second pause between two stimulus to avoid interruptions for participants' reactions. Altogether, the stimulation session lasted for 40–60 seconds. After another 10 to 20 seconds, we asked the participant to fill out a questionnaire. The time gap between the stimulation session and the questionnaire was selected to avoid interruption for participants' reactions after stimulation. The entire session was videotaped to capture the participants' facial expressions and behaviour.

Data Gathering: The SC is mainly governed by the sympathetic branch of the human body's autonomic nervous system. Prior research has shown that emotional arousal can be often indicated by measuring SC [3, 10, 28]. Hence, we used the Empatica E4 wristband to collect the participant's SC during stimulation. In the questionnaire, we asked the participant to rate how they felt during the stimulation in a 7-point Likert scale in terms of Valence (1 - *Very Unpleasant / Negative Valence*, 7 - *Very Pleasant / Positive Valence*), arousal- (1 - *Low Energy / Low Arousal*, 7 - *Very Energetic / High Arousal*), Stress (1 - *Not Stressed at all*, 7 - *Very Stressed*). These questions were adapted from prior work to get a reflection about the subject's emotional state [6, 11, 60] during the study. Also, we asked the participant to describe what they felt during the stimulation. Similar to the previous study, we also analysed the videotapes in a post-processing manner and rated our observations on a 5-point "behavioural scale" (0- *No apparent response*, 1- *Voiceless smile*, 2- *Laughter*, 3- *Laughter, twisting, and wiggling in response to the stimulus*, 4- *laughter and subjects pulls limb away from tickling device*).

3.7.2 Data Analysis and Results.

Skin Conductance: The number of spontaneous fluctuations in SC, also known as SCR-peaks (SCR_p), and the overall level of skin conductance (SCL), is the most common feature used to describe emotional arousal [3, 10, 28]. Using MATLAB, Ledalab toolbox, we did a continuous deconvolution analysis which divided the SC signal into phasic and tonic components. Then, the number of SCR-peaks was counted during the baseline and during stimulation. If entire stimulation session lasted for less than 60 seconds, the baseline duration for the analysis was adjusted accordingly. For example, if the stimulation session lasted for 40 seconds, the last 40 seconds of the baseline was taken for the analysis. Finally, the difference between mean SCL during the baseline and during the stimulation was calculated. The results show that except for three participants

(P3, P4, P7), all other participants have a higher number of SCR-peaks than the baseline. The mean difference of number of SCR-peaks between stimulation and baseline is $M = 4$ ($SD = 4.80$). The high standard deviation is due to three participants (P2, P8, P11), indicating a very high number of SCR-peaks compared to the baseline. Also, except for P3, all the other participants indicated a higher average SCL compared to the baseline ($M = 0.24$ $SD = 0.45$). The higher standard deviation is due to two participants (P2, P8) showing a very high mean SCL than the baseline. All these changes in the number of SCR-peaks and mean SCL are an indication of emotional arousal [10]. Most of participants (9 out of 12) experienced an emotion elicitation during stimulation. P3, P4, and P7 have demonstrated a lower number of SCR-peaks or lower SCL rise, demonstrating lower arousal.

Self Ratings, Self Description, and Behavioural Assesment: Overall, all the participants rated the feeling of the stimulation to be very pleasant ($M = 6.0$; $SD = 0.73$) indicating a positive valence. However, this may be because the majority of participants felt pleasant at the beginning of the study, and such emotion remained during stimulation. The mean rating for arousal is also positive ($M = 5.08$; $SD = 1.97$). Also, all participants agreed that the stimulation did not cause stress ($M = 1.50$; $SD = 0.66$). Similar to valence, this may be because the majority of participants felt pleasant and relaxed at the beginning of the study. Only three participants (P3, P4, P7) had rated lower arousal levels (<4 in a 7-point Likert Scale), while all the other participants had rated a higher arousal level (>4 in a 7-point Likert scale). This was also evident in the higher number of SCR-peaks compared to baseline by all the participants except for P3, P4, and P7.

Finally, we analysed how participants described the stimulation. All participants included the word "Tickling" or "Ticklish" in their description. The majority (10 out of 12) of them used words such as *"fun"*, *"laugh"*, *"nice"*, *"good"*, *"pleasant"*, *"enjoyable"*, *"happy"*, *"joyful"*, *"interesting"* in their description, which may be related to a higher arousal and positive valence. For example, P1: *"It was ticklish, but it felt quite nice, fun and interesting"*. P5: *"The actuation was really tickling... It was subtle and really pleasant, enjoyable tickling and I had to start smiling..."* P12: *"it was a nice tickling feeling. I like the sensation. It made me laugh. I think it's fun and joyful"*. Also, three participants described how unexpected the stimulation was and how it made them laugh or smile. P2 : *"It was heavily ticklish and made me laugh. I didn't expect it!"*, P9 : *"I felt a bit surprised initially with the tickling feeling which made me smile and appreciate the sensation..."*. Furthermore, two participants used low arousal words such as "relaxing" or "calming". For instance, P3: *"It was good, a bit ticklish, but more like a relaxing massage"* , P7: *" Enjoyable tickling, it was like relaxing massage for me"*. This description also matched the low self-rated arousal level and lower number of SCR-peaks of P3 and P7, showing they experienced the stimulation in a more relaxing manner.

The overall 5-point behavioural scale depicts that, in general, participants tend to laugh when receiving the stimulus ($M = 1.91$, $SD = 0.66$). 7 out of 12 participants laughed during the stimulation. Also, two participants showed laughter, twisting, and wiggling response. Three participants made voiceless smiles.

3.8 Insights and Example Applications

The results of the studies (See Figure 8) shows that most of the "Circular" patterns rated consistently higher self-perceived ticklishness. Among those patterns, BCF2 demonstrated a significantly higher ticklishness. The reason behind this could be mainly for general lower rotation frequency of "Circular" patterns, such as CF1: 1.2 Hz, CF2: 2.4 HZ, and CF3: 3.2 Hz. This finding is further confirmed by observing that low frequency (SF1 = 3hz) of the "Straight" pattern demonstrated a higher ticklishness among "Straight" patterns. These frequencies may mimic a similar speed or frequency of a human tickling action.

Also, the participants' feedback and the 5-point behaviour scale results in study 2 and study 3 demonstrated that the identified tickling pattern (BCF2) could evoke laughter. A similar reaction can be seen in a gargelesis tickling described in literature [33]. The reason for this could be because tickling multiple locations at the same time mimics human tickling. This was further evidenced by qualitative feedback some participants provided. For instance, *"When the tickling sensation is at the highest point, I found it more playful, and it made me laugh, and I felt it like someone else is tickling my foot"*.

All participants mentioned that the actuated stimulus created a ticklish sensation. Sometimes tickling can also be unbearable and unpleasant, especially when it creates knismesis tickling [33] or when the person is in a bad mood. Hence, the positive valence ratings and lack of stress elicited from stimulation may result from participants being in a good mood at the beginning of the study. Further studies are required to confirm how the stimulation would work if participants are in a bad mood before stimulation. Also, the majority of participants used terms such as "fun", "enjoyable", "joyful" to describe the identified tickling sensation that evoked laughter. However, laughter may also occur due to the awkwardness of tickling, depending on the situation and the context. Further evidence is required to confirm that the evoked laughter is due to fun and enjoyment.

Our work presents a tickling actuator and stimulation parameters that can evoke laughter. In the final study, we confirmed that it could successfully elicit laughter. According to participants' descriptions about the stimulation they felt, the tickling experience was fun and enjoyable. However, it is crucial to identify how digital tickling is beneficial and applicable, as ticklish laughter is not considered a pleasant experience for the person who gets tickled in some situations. According to literature [34], tickling, which elicits laughter, is a fun and pleasurable experience when consensual and occurs between people with positive social relationships. Participant reports that the tickling sensation was fun and enjoyable may be because they provided consent for the study and the positive rapport that they developed with the experimenter at the beginning of the study. For example, in study 1 and study 2, participants already knew they would experience a tickling sensation. In study 3, they were aware that we would provide them a stimulation that will not harm them. When tickling is non-consensual, sometimes it can be considered unpleasant and torturous [79]. Furthermore, according to literature, although a person's laughter when tickled is similar to the laughter elicited from a comedy or joke, the inner experience of getting tickled may be unpleasant [34]. Reports also show that prolonged tickling can be highly unpleasant and considered torturous. Hence, it is important to identify applications in which ticklefoot can create a positive human experience. According to the literature and our participants' feedback, we determined that our stimulation will generate the most pleasant and fun experience if participants feel that the device is controlled by a person they have a positive relationship with. Moreover, since prolonged tickling may be considered unpleasant or torturous, it is also essential to control the tickling time.

Finally, based on the above insights and participants' feedback, we derived three application possibilities for a wearable tickling device in the context of non-verbal remote affective communication, entertainment, and well-being (See Figure 10). As mentioned earlier, non-consensual tickling can be considered unpleasant and torturous [79]. Hence, all the applications selected are related to consensual tickling that will result in a pleasant experience.

Remote Playful Interactions for Couples: During the emotion exploration study, both female and male participants found that the interface's stimulation is fun and enjoyable. Moreover, all the participants were laughing or smiling. One participant also mentioned it triggered old memories associated with tickling and having fun with his partner. P10: *"it was tickling and kind of fun and happy, it probably triggered old memories associated with tickling and having fun"* . This comment shows that we can use the device's fun and joyful experience coupled with the interpersonal quality of tickling for remote non-verbal playful interactions that we usually have with our loved ones (See Figure 10(A)). Such an application is highly applicable during social distancing. Hence,

Fig. 10. The figure shows the example applications of TicklingInsole derived from participants' comments and feedback. (A) Remote playful interactions for couples. (B) Eliciting mirthful responses during an entertaining movie. (C) Creating distractions to release stress.

such an interface can support playful interactions between couples, particularly for long-distance remote playful interactions. Such a device will contribute to a wide range of interfaces that supports remote affective communication in HCI [76].

Eliciting Mirthful Responses for Entertainment: In general, participants laughed during the stimulation, especially when it was unexpected. This response can be useful to elicit sudden mirthful responses during entertainment sessions, such as movies, in 4D cinemas, or virtual reality. Prior work has also investigated how tickling can elicit mirthful behaviours, which has demonstrated promising results [26]. Moreover, due to the wearable form-factor, it could be easily integrated into a home theatre system (See Figure 10(B)). Also, a participant commented that he could relate the tickling sensation to a fish pedicure that he had experienced before. *"I felt tickling. Similar to a fish pedicure. It was fun to remember that experience"*. This comment implies that the interface can be used in fun immersive VR/AR applications where feet are involved.

For Releasing Stress: A participant who laughed while twisting and wiggling (P8) mentioned that it helped her create temporary distractions and enjoy the moment. P8 *"Actually, when stimulation starts, the focus went to my feet due to tickling and forgot whatever was in my mind. Technically it just distracted my mind from whatever it was already in it"*. Hence, we believe such an interface can reduce stress by creating distractions. Prior research has also shown that tickling and laughing can release stress [24, 33, 82]. However, further studies are required to confirm whether tickle-foot's tickling stimulation can relieve stress. Also, some participants identified that the sensation is calming and relaxing, which is certainly useful in reducing stress. The same actuation may be used as a proper foot massaging device by modifying the end trigger from a brush to a ball (See Figure 10(C)).

3.9 Prototype

This section demonstrates the potential of a wearable tickling device that evokes laughter and fun, supporting the derived applications above. The prototype's design was informed by a number of requirements and a series of user studies, which we outlined in previous sections. Our prototype (see Figure 11) has three actuators, placed at locations considered most ticklish based on the findings of our studies. The actuators are embedded in a flexible insole, preventing constraints on the user's gait. For proper heat dissipation, a non-conductive flexible aluminium tape layer was attached to the bottom of the insole. A middle flexible silicon layer acts as a barrier to avoid magnets falling out from the insole while walking. The brushes are attached to springs to ensure these slightly touch the sole of the foot. The prototype is powered by a High-Drain 3.7V Lithium-ion battery (18650) with a maximum discharge rate of 20A. The current prototype drains about 6A. This means the device can last for 60 minutes with two parallel connected batteries.

Fig. 11. Ticklinginsole prototype and the layered architecture of it: 1. Flexible 3D printed NinjaFlex insole cover (2 mm), 2. Flexible silicon layer acts as a barrier for magnets (0.5 mm), which will avoid magnets coming out from the insole 3. Flexible NinjaFlex layer, which integrates PCB modules and wire cables (5 mm), 4. Flexible Aluminium heat dissipation layer (0.5 mm). The overall thickness is 8 mm.

Fig. 12. User reactions for the insole prototype (UK size 9-10) while they are experiencing it.

Initial User Reactions. The studies which informed the insole design were conducted using adjustable testbeds. In this way, we were able to recruit participants with a wide range of foot-size for parameter tuning. After tuning parameters, we developed the final prototype for UK size 9-10 and gave it to six participants (three Females) aged between 24 and 34 (M = 28.6 ; SD =3.0) with matching foot size to test. Among these participants, four have not participated in any previous studies, while two participated in study 2. They tested the prototype while in a sitting posture. We recorded their reactions and rated the reactions according to 5-point "behavioural scale" (0- *No apparent response*, 1- *Voiceless smile*, 2- *Laughter*, 3- *Laughter, twisting and wiggling in response to the stimulus*, 4- *laughter and subject pulls limb away from tickling device*). Five of them laughed while one participant reacted with a voiceless smile confirming our final prototype could deliver expected results. The reactions some participants had to the prototype's stimulations are shown in Figure 12. These images are included with their informed consent. Moreover, they tested the prototype in different inclinations of the foot. When the insole's inclination is higher than 30°, the actuation was not optimal.

4 LIMITATIONS AND FUTURE WORK

There are several technical limitations in the current design, which we will address in the future. For example, the system currently draws a current closer to 6A, which can be further reduced by increasing the number of turns in a coil. By doing this, the actuators can generate the same magnetic field by using less current. To increase the number of turns of a coil, we can either increase the number of layers of a single coil or reduce each trace's width and reduce the distance between two traces. Both of these methods will require a better PCB manufacturing process, which may increase the cost. Hence, a tradeoff between reducing current and increasing the manufacturing cost has to be balanced. Also, the current actuator does not utilise a feedback control loop for controlling the magnet. In the future, we aim at including a feedback control mechanism, such as PID, to improve system performance. For the feedback control loop, we need to sense the magnet's location, which could be achieved by integrating a Hall effect sensor. Moreover, current brushes are off-the-shelf paintbrushes. In our pilots, we only investigated round brushes with two different sizes (2, 4) and two different materials (golden sable hair, nylon). The length of the hair was about 1 cm. However, there are various brushes with other sizes covering different areas with different hair lengths. Hence, we did not investigate how other different brushes with different areas and length may affect tickling feedback. However, it is possible to manufacture customised brushes, particularly tailored for this type of application. Using brushes tailored for this particular application may even elicit a better sensation. Customised brushes may also allow us to reduce the brush height, which will eventually reduce the overall thickness of the artifact. Furthermore, thinner magnets that provide the same pull force will reduce the form factor's thickness. The current magnet is an N45 grade magnet with a thickness of 4 mm. There are N52 magnets with the same pull force with a thickness of 2 mm. Such a magnet will reduce the thickness of the form factor by 2 mm.

The final prototype still works with small bends of the insole, lower than 30°. However, when the insole's inclination is higher than 30°, the actuation is not optimal. Hence, the current prototype works best while in a sitting posture. The suggested applications are also proposed to use the interface in sitting posture. Also, we do not aim at tickling while standing or walking. Furthermore, it might be unsafe to tickle while walking as it may change the gait. However, the users can still stand and walk while wearing it without the actuation.

The durability of the current prototype has not been severely tested yet. Although the current PCBs are rigid, we achieved enough flexibility in the prototype by embedding actuators into a flexible insole. In the future, we plan to further improve flexibility by using a flexible PCB covered inside a flexible silicon layer. Also, to protect against humidity and sweat, PCBs can be manufactured with moisture protection, such as lamination. Also, to prevent any extra pressure exerted on the magnet, the brushes can mount on top of a spring or a pressure absorbing form. In this way, we can reduce the extra friction that may occur due to pressure exerted on the brush. In the future, we plan to develop a durable high fidelity prototype with the improvements mentioned above.

Moreover, in the future, we want to conduct an in-depth investigation of the potential use cases we identified. We plan to explore further how TickleFoot can enhance 3D and 4D movie enjoyment by blending with visual and auditory feedback. Also, the integration of TickleFoot into VR may enhance remote playful interactions between couples. Also, a careful improvement in the end trigger (such as a ball instead of a brush) will open up many possibilities in therapeutic applications, such as in remote physiotherapy for the elderly, especially during social distancing [32]. The device's ability to stimulate foot's sensory extremities will open up possibilities of passive haptic rehabilitation [69] for lower extremity. Another future work is to investigate the possibility of connecting TickleFoot with a suitable stress estimation method [23, 38] to activate stress release based on stress levels. Furthermore, in a future implementation, we will include an IMU-based motion-sensing mechanism to automatically identify users' uncomfortable reactions to tickling and shift the tickling pattern to be more pleasant. In this way, we can reduce subjective discomforts to tickling.

5 CONCLUSION

In this article, we present TickleFoot, a foot-tickling mechanism that can tickle the sole of the foot to evoke laughter. We first developed an actuation mechanism, creating tickling sensations along the foot. We then conducted two user studies, investigating the most tickling locations of the sole and identifying design parameters such as stroke frequency and spatial patterns that can evoke laughter. In a subsequent study, with a new set of participants, we confirmed that our design could elicit a sense of fun and laughter. User feedback implied that our device would be useful in playful interactions connected with fun and laughter, such as remote interactions between loved ones, releasing stress, or eliciting mirthful entertainment reactions. Finally, we develop an insole integrating our actuators to demonstrate the potential of the wearable tickling device. We believe our work will inspire future wearable interfaces that support playful interactions between individuals.

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