A Vibrotactile Vest for Remote Human-Dog Communication

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***Abstract*— Dogs have been helping humans in different ways since prehistoric times. Modern working dogs perform tasks ranging from search-and-rescue to bomb detection, but relatively little work has been done on the use of technology with working dogs. Therefore, communication with working dogs is still predominantly visual and audial. In this paper, we introduce a vest with four embedded vibration motors in specially designed motor housings. The vest applies vibrotactile cues to the dog that wears it, and the dog is trained to associate the cues with practical commands. The commands are issued to the vest from a handler with a wireless remote. We demonstrate the vest using a test subject: a six year old male Labrador Retriever/German Shepherd Dog crossbreed. We test the perception threshold of the test subject to haptic cues, and its proficiency in understanding several haptic cues. These cues differ in location and/or waveform. Our case study shows that the dog was able to successfully learn haptic commands in this way. This apparatus may prove beneficial for search and rescue purposes, working dog operation, training deaf dogs, and training by handlers with speech impairments.**

I. INTRODUCTION

Humans have been increasingly interacting with dogs (*canis familiaris*) ever since their domestication approximately 15,000 years ago. This interaction is characterized by humans training the dogs to act in a desirable fashion, most often as companions. Specialized training can be implemented to produce working dogs, such as Search and Rescue (SAR) dogs, Military Working Dogs (MWD), seeing-eye dogs or therapeutic dogs [1].

Canines have significant physiological advantages over humans (scent, hearing), which incentivizes us to use them for jobs we cannot do ourselves; such as detecting explosives or searching narrow spaces. When considering the use of robots for such tasks, we find that dogs have far superior motility. For instance, traversing sand or steps is easy for a dog, but nearly impossible for most robots. This motility limitation of robots makes them extremely difficult to use in complex or dynamic environments. Considering that neither humans nor robots can perform the tasks dogs can, it is no surprise that the uses for working dogs have only increased as we better understand how to work with them.

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Dogs have not changed much in the past few centuries, but technology certainly has. Machines have entered almost every aspect of our life, allowing us to perform otherwise impossible tasks. Technology has made it so that most of our communication is done electronically rather than verbally, allowing us to transcend distance and language barriers. Why, then, do we not use communication technology with dogs to accomplish new and important tasks?

Information can be transmitted through any of the senses, although the most common forms of transmission are visual and audial. In recent years, touch has been increasingly used to transmit information as an alternative to the traditional visual and auditory methods. Tactile stimulation is a powerful tool which has been found to be useful in humans and human-robot interaction. Examples include tactile feedback to teach arm motions [2], cueing workers on important environmental events [3], improving task dexterity [4], providing feedback from prostheses [5], assisting in navigation [6], [7], teleoperation [8], [9], and the list goes on. It is entirely possible, in our view, that dogs may undergo haptic learning in much the same way. In other words, haptic cues may prove a viable tool for human-dog interactions. Communicating with dogs via haptic rather than auditory cues may improve command execution, as there exist fewer distraction stimuli in the perception modality relevant to the signal (literally, less noise).

Most of the work on the digitization of dog training has focused on either behavior assessment or on trainer response. E.g., devices have been constructed to provide automatized posture detection information (behavior assessment) or provide automatized punishment in the form of aversive electric shocks (trainer response) [10], [11]. Indeed, the most relevant US patents having to do with dog training (e.g. [12]) all focus on response to animal behavior in the form of aversive electric shocks or feeding. Recently, haptic communication with dogs has started to gain attention. Britt et al. have used vibrotactile stimulation paired with audial cues to guide a dog to desired locations using GPS [13]. [14] have also suggested the use of vibration motors in digitized dog vests to convey haptic commands. Byrne et al. have recently evaluated the canine ability to detect vibrotactile stimulation [15]. A vibration motor was attached to the fur of several dogs, and their signal Perception Threshold (PT) [16] of vibration was measured. In another study, Byrne et el. have demonstrated a dog's ability to associate two distinct haptic cues with desired behaviors [17]. Two vibration motors were embedded in a vest worn by a dog; the vibration motors were placed on either side of the dog. The dog was tasked to touch a ball on its right or left, by vibration of the associated motor. Byrne's work shows the potential for human-dog communication via haptics.

A small number of vibration motors can be used to convey a large variety of commands. Humans are able to discriminate between different vibration locations [18], pulse frequencies [19] and waveform [20]. We hypothesize that canines will be able to discriminate between different vibrotactile cues in a similar fashion.

In this paper, we introduce a wearable haptic device for dogs. Our device is used to remotely communicate commands based on painless vibrotactile stimulation; i.e. vibration applied on the back and sides of the dog at four possible points. Our work will corroborate the works of Byrne et al., and expand it in several ways. Firstly, in [17] vibration motors are placed tightly against bony areas of the dog; in [15] the vibration motor is directly attached to the fur of the dogs by an alligator clip. In our work, we introduce a pronged vibration-motor housing that allows imprecise placement of the vibration motor. Furthermore, in [17] the haptic commands are spatially coded. I.e., the dog is trained to touch a ball on its right if it feels a vibration on its right side, and vice versa. In our work, we demonstrate the ability of a dog to learn several distinct commands that are unrelated to the location of the vibrotactile stimuli. Lastly, we introduce haptic cues that differ temporally. Two haptic cues will be applied to the same place on the dog, but with different temporal modulation (constant and pulsing). The dog will be taught to associate each cue with a different command. This will show the potential to transmit a large number of commands using a small amount of vibration motors.

The remainder of this paper is organized as follows. The design of this device is detailed in Section II. Sections III and IV demonstrate the capabilities of the device on a single canine subject in four experiments. Firstly, we evaluate the dog's PT to vibration stimulus. Next, we compare the dog's aptitude in responding to haptic commands, relative to vocal commands. We then demonstrate the dog's ability to discern between two haptic commands that differ in vibration location. This demonstrates that a dog can be trained to understand distinct haptic cues and perform corresponding tasks; thus the concept of haptic communication with dogs is feasible. We finally demonstrate the ability of the dog to discern between two haptic commands that differ temporally. In Section V we discuss our findings.

II. Device Design

We designed a haptic communication device that is based on a commercially available fabric-vest. The vest is augmented with a receiver unit and four vibration motors (ERM, 10 mm diameter, 3 mm thick). A separate, handheld transmitter is used to transmit commands to the vest. This transmitter is operated by the human handler, while the dog wears the vest. Communication between the transmitter and receiver is accomplished by RF signals, using coil antennae at each end. This configuration allows the handler to transmit a variety of commands to the dog without a line-of-sight, and at ranges of up to 30 m.

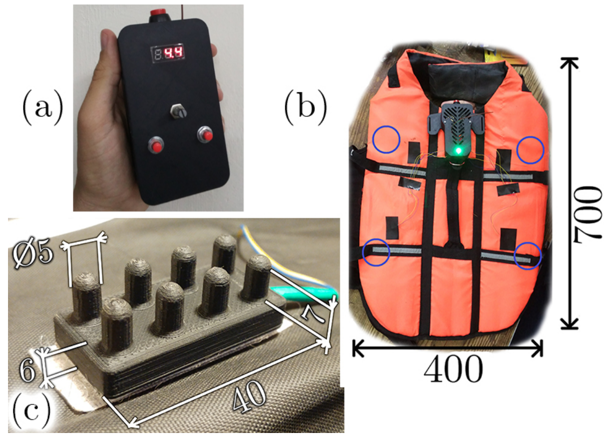

Fig. 1. (a) The transmitter has two buttons (red) at the bottom. The amplitude dial is in the center, and the amplitude is displayed on a screen (top). (b) The receiver vest has a receiving unit (black with green LED) that receives commands from the transmitter and activates embedded vibration motors (locations marked in blue circles). (c) The vibration motor housing has prongs that are intended to penetrate the fur and deliver the vibration to the skin. All dimensions are in mm.

The transmitter interface has two buttons, a dial and a simple screen. The two buttons are used to select and transmit commands, while the dial is used to set variables for our experiments, as will be detailed in the next section. The screen shows the user the exact dial position, for experimental purposes as well. When a button is pressed, an internal microcontroller (Arduino Uno) sends a command using a simple 433MHz transmitter, shown in Fig. 1.

The vest is made of fabric to conform to the dog's body. We embedded four vibration motors in pronged plastic-housings (Fig. 1), and placed them on the front-right, front-left, rear-right and rear-left of the vest, as shown in Fig. 1. A microcontroller (Arduino Nano) with an external LED is placed in a plastic case on the vest as well. This microcontroller receives the commands from the transmitter, interprets them, and activates the corresponding vibration motors with independent PWM voltage. In this way, the vest can transmit any imaginable combination of vibrations to the dog that would correspond to commands.

An early version of the vest used simple fabric encasings for the vibration motors. Early trials with these encasings led us to believe that the test subject could easily feel the two front vibration motors, but rarely the hind motors. The front motors were placed closer to bony areas with thinner fur, while the rear motors were placed on non-bony areas with thicker fur. Furthermore, the vest does not fully conform to the dog's body, and there were small gaps between the vest and the dog, especially at the vicinity of the rear motors. These issues motivated us to change the motor encasing, from a soft encapsulation to a rigid housing specially designed to deliver vibrations more directly to the skin. The inspiration for the new vibration motor housing comes from dry electrodes, e.g. [21]. The geometry of the new design penetrates the fur, allowing more direct contact with skin. We 3D printed motor housings (depicted in Fig. 1), and embedded the vibration motors in a press fit to ensure

Fig. 2. The test subject wearing the vibrotactile vest. The receiving unit (black with green LED) receives the commands from the transmitter and activates embedded vibration motors. Basic body dimensions are shown in mm.

good transfer of energy from the motor to the housing.

The weight of the receiver and the vibration motors is 185 g. The weight of the vest without the receiver is 255 g. The commonly accepted weight for an adult dog to carry is 10% of its own weight. Considering that our test subject weighs 35 kg, the weight of the system (440 g in total) is inconsequential. The receiver is 3D printed and attaches to the vest using velcro and a fastening ring.

A dial on the transmitter can be used to control the desired vibration amplitude, represented as a voltage from 0 to 5 V, and displayed on the transmitter screen. The receiver is pre-programmed with different stimulation patterns that correspond to the buttons and dial position. For example, when the button corresponding with the "spin" command is pressed, the receiver activates the front-right motor in the vest. The motor is energized for 1.5 seconds at the amplitude given by the required voltage. The receiver vest illuminates the RGB LED with a color distinct to the command during execution, providing a visual cue that the command is in process (motors are vibrating). The light is located on the back side of the dog's neck, so that the dog can not see the visual cue. When no command is issued, the LED is illuminated green. The test subject wearing the vest is shown in Fig. 2.

In our demonstrations, four distinct commands are programmed in the remote and vest. These commands are summarized in Table I. The commands are as follows. A "Spin" command orders the dog to turn around; the corresponding cue is a constant vibration of the front-right motor for a duration of 1.5 s. The user presses the right button on the remote to issue this command, and may select the vibration amplitude using the dial. A "Down" command orders the dog to lie down; the corresponding cue is a constant vibration of the two rear motors for a duration of 1.5 s. The user presses the left button to issue this command, and may select the vibration amplitude using the dial. A "To me" command orders the dog to approach the handler; the corresponding cue is a pulsing vibration of the front-left motor in three square waves, with a pulse width of 200 ms, 50% duty cycle. The user presses both buttons to issue this command, and may select the vibration amplitude using the dial. A "Backpedal" command orders the dog to walk backwards; the corresponding cue is a pulsing vibration of the front-right motor in four square waves, with a pulse width of 215 ms, 50% duty cycle. The user presses the right button to issue this command, with the dial set to '0'.

TABLE I
POSSIBLE COMMANDS AND CORRESPONDING CUES

Command	Description	Cue Location	Vibration Type
Spin	Turn around	Front-Right	Constant
Down	Lie down	Rear-Both	Constant
To me	Approach handler	Front-Left	Pulsing
Backpedal	Walk backward	Front-Right	Pulsing

III. METHODS

The dog used for the trials is shown in Fig. 2. The subject is a six year old male Labrador Retriever/ German Shepherd-Dog cross. These two breeds are widely used as working dogs for SAR, MWD and other tasks. The subject's fur type is a long double-coat. The subject was raised to be a seeing-eye dog for the blind, but was ultimately deemed unfit for the job after a month in the training course. Aside from this course, the subject has received no professional training.

All of the experiments performed were approved by the Ben-Gurion University Committee for the Ethical Care and Use of Animals in Research and the Israeli Ministry of Health, application IL-81-12-2016. Training and trials were done using positive re-enforcement, rewarding successful completion of tasks with edible treats. The experiments were non-invasive and did not involve any pain or observed discomfort.

The training and test procedure was as follows: first, the subject was accustomed to the vest and experimental environment. Next, he was trained to associate the "Spin" vibration command (see Table I) with a previously learned vocal command. This training took about one hour until consistent responses were demonstrated. Following training, vocal and haptic commands were issued to quantify the response rate. This is detailed in Section III-B. All commands, haptic and vocal, were issued when the test subject was in a stationary standing position.

After establishing the haptic response rate, the dog's PT was measured. PT is the minimaly detectable vibration intensity. The procedure is detailed in Section III-A.

At this point, the dog was well accustomed to one haptic command. We then proceeded to teach a second command, "down". This command was taught over the course of three hours, partly due to technical difficulties. A response test to both haptic commands was then performed (Section III-C) to verify the ability of the dog to distinguish between the two haptic cues and associate them with the proper commands.

Next, the test subject was taught a third haptic command "to me", although this command was ultimately not used for experiments. The training duration was approximately fifteen minutes until consistent responses were demonstrated. Finally, a fourth haptic command "backpedal" was taught. This last haptic cue has the same location as the "spin" command cue, with different temporal modulation (pulsing rather than constant). The training duration was approximately two hours. As before, a response test was performed (Section III-C) to verify the dog's ability to distinguish between the two types of haptic cues– pulsing and constant vibration.

During experiments, a 'handler' attracts the dog's attention, gives vocal commands when necessary and rewards desired behavior. An 'experimenter' remotely applies the stimulus with the transmitter based on a predefined protocol. The handler was blind to timing of the next command and the command type.

A. Psychophysical Evaluation - Perception Threshold and Experimental Blindness Validation

We wished to establish the test dog's PT for vibrotactile stimulation. This is the weakest signal that the dog can perceive. In establishing this threshold, we suspected that repetitive vibrotactile stimulation may encourage false positive behavior, disrupting our threshold analysis. To overcome this, we subjected the dog to different vibration amplitudes with the front-right motor in the range (0 g, 2.13 g), in a uniformly random manner. Vibration amplitudes were premeasured by attaching an IMU to the housing. The threshold was then calculated by averaging the lowest acceleration for which the correct behavior (spinning) was exhibited, and the highest acceleration for which the behavior was not exhibited. The results of this experiment are shown in Fig. 3.

An issue in perception experimentation is that the handler may inadvertently convey information to the subject in a subconscious way. This is sometimes known as the "Clever Hans Phenomenon" [22]. This phenomenon addresses the issue of test subjects (especially animals) observing the experimenter's subconscious behavior, instead of the intended signal, and acting accordingly. In our experiment, we use the PT evaluation to verify the absence of this effect. Consistent PT results will indicate experiment 'blindness'.

B. Response to a Haptic vs Vocal Command

In our experiment design, we followed Signal Detection Theory. Both vocal and haptic "spin" commands were issued at a random order. Following an initial raising of the dog's attention (calling its name), its reactions were recorded as success/failure according to command/no-command given; i.e., when a command was given, "success" was when the dog performed a spin, while the dog's lack of spinning was recorded as a "failure". When no command was given, "success" was dog's lack of spinning, while spinning was recorded as "failure". Each of the responses could fall in one of four categories: true positive (Hit), false positive (False Alarm; FA), true negative (Correct Rejection; CR) and false negative (Miss). Rates were recorded and further

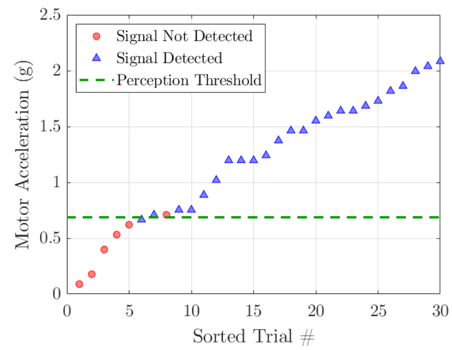

Fig. 3. Experimental results for the vibrotactile stimulation perception threshold in a canine subject. The trials were conducted in random order, but are displayed by order of amplitude.

analyzed, generating Receiver Operating Curves (ROC). The True Positive Ratio (TPR) is computed by $\text{TPR} = \frac{\text{HIT}}{\text{HIT+MISS}}$. The False Positive Ratio (FPR) is computed by $\text{FPR} = \frac{\text{FA}}{\text{FA+CR}}$. The Positive Likelihood Ratio (PLR) is computed by $\text{PLR} = \frac{\text{TPR}}{\text{FPR}}$. These ratios are indicative of the subject's perceptual detection of stimuli.

The Discriminability (d') of a signal is estimated by distance between data point and baseline diagonal (i.e., the perpendicular to the diagonal). The Criterion c is the point above which percepts are deemed to consist of "noise+signal" and below which percepts are deemed "noise".

C. Response to Two Spatially Different Haptic Commands

To understand the ability to discriminate between two spatially different haptic cues, we performed a demonstration where the subject was randomly given either a haptic "spin" command, a haptic "down" command, or a different known vocal command (e.g. "sit"). At this point in the experiment, the dog was only familiar with these two haptic commands. 15 commands of each type were given, for a total of 45 commands in the demonstration. Here we are interested in seeing the dog's ability to tell two spatially distinct haptic commands apart; and whether the introduction of a second haptic command interfered with the former haptic command. To evaluate the interference of a second command, we conduct a χ^2 test to determine whether the success rates for the "spin" command were impacted by training a second haptic command.

D. Response to Two Temporally Different Haptic Commands

To understand the ability to discriminate between two temporally different haptic cues, we performed a demonstration where the subject was randomly given either a haptic "spin" command or a haptic "backpedal" command. The former uses a constant vibration, while the latter uses a pulsing vibration, with a common duration of 1.5 s. At this point in the experiment, the dog was familiar with all four haptic commands detailed in Table I. 15 "spin" and 15 "down" commands were issued in random order, and responses were recorded. Here too we used a χ^2 test to determine whether the success rates for the "spin" command were impacted by training a temporally different haptic command.

TABLE II

VOCAL AND VIBROTACTILE COMMAND RESPONSES

Vocal Commands			
Command Issued\Performed	**Yes**	**No**	**Result**
Yes	HIT=15	MISS=3	TPR=0.833
No	FA=2	CR=10	FPR = 0.167
Vibrotactile Commands			
Command Issued\Performed	**Yes**	**No**	**Result**
Yes	HIT=17	MISS=1	TPR=0.933
No	FA=4	CR=8	FPR = 0.333

IV. RESULTS

In this section, we present the results of our experiments, by order of presentation in the previous section.

A. Psychophysical Evaluation - Perception Threshold and Experimental Blindness Validation

The vibrotactile stimulation PT was estimated as motor acceleration, measured in g-force. The threshold for our canine subject was found to be 0.69 g, see Fig. 3. Byrne et al. [15] reported an average PT of 3.94 g for a successful detection rate of 90%. We performed an additional PT experiment using a vibration motor housing without prongs, resulting in a significantly lower PT (not shown). The lower threshold results suggest that the prongs improve performance in comparison to other vibrotactile application methods.

As for the “Clever Hans Phenomenon”, the consistent measurement of the PT is a testament to the ‘blindness’ of the experiment. If the handler were to give subconscious cues to the dog, commands would have been performed at sub-threshold vibration intensities. The fact that the dog did not react to low-intensity vibrations is evidence that no subconscious cues were given.

B. Response to a Haptic vs Vocal Command

For both vocal and vibrotactile commands, the dog exhibited high sensitivity. The test subject answered appropriately in 25/30 (83.33%) trials in both cases. The results appear in Table II. The corresponding ROCs appear in Fig. 4.

Observing the ROC in the vocal case, the diagonal and its perpendicular d' intersect exactly at $(0.5, 0.5)$, i.e. the criterion c falls square halfway between signal and noise distributions, suggesting that the subject’s aural perception is that half of all auditory signals are noise and half are target signals (on average). Therefore, $c = 0.5$. The discriminability is found to be $d'_{Vocal} = 0.471$. Similarly, in the vibrotactile case $d'_{Vibrotactile} = 0.426$, and $c = 0.63$. The higher value of c in the vibrotactile case suggests that the subject dog’s perception is that, on average, vibrotactile cues are more often signals than noise. Experiments with multiple canine subjects are needed to truly characterize the differences in perception and discrimination of vocal and haptic commands.

As apparent from the ROCs and the raw data, for haptic communication, the subject’s decision criterion was lowered. I.e, bias towards a “yes” answer was developed, as is attested

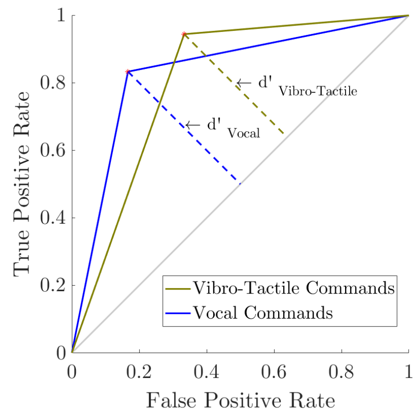

Fig. 4. The ROCs for the test subject’s response to vocal and vibrotactile commands, for 30 trials.

TABLE III

TWO SPATIALLY SEPERATE HAPTIC COMMAND RESPONSE

Command Issued\Performed	**Spin**	**Down**	**No Response**
Spin	13	2	0
Down	2	11	2

TABLE IV

TWO TEMPORALLY SEPARATE HAPTIC COMMAND RESPONSE

Command Issued\Performed	**Spin**	**Backpedal**	**No Response**
Spin	10	3	2
Backpedal	3	11	1

by an increase in amount of HITs as well as in FAs (and, respectively, by a decrease in MISS and CR rates).

C. Response to Two Spatially Different Haptic Commands

The results of the two haptic commands test appear in Table III, and clearly show successful execution and differentiation between the two commands. To examine performance under knowledge of one and two haptic commands, we compared the success rate of the haptic “spin” command as the only known command with the success rate as one of two known commands. The success rate of a single command was TPR $= 0.933$. The success rate of the two commands was computed as the amount of correct “spin” responses out of all “spin” commands issued (TPR $= \frac{13}{15} = 0.866$). A χ^2 test results in $\chi^2_2 = 0.599$, $p = 0.439$; i.e., the difference between proportions was not significant.

D. Response to Two Temporally Different Haptic Commands

The results of the two haptic commands test appear in Table IV, and indicate successful execution and differentiation. Similarly to the spatially different haptic cues, we want to determine the performance deterioration caused by teaching a possibly confusing command. We compared the success rates of the haptic “spin” command as measured in Table III. This success rate is chosen because it represents the success rate of the “spin” command prior to learning the “backpedal” command. The success rate of a “spin” command was TPR $=$ 0.867. The success rate of the two commands was calculated as the amount of correct "spin" responses out of all issued "spin" commands (TPR $= \frac{10}{15} = 0.667$). A χ^2 test results in $\chi^2_2 = 1.677$, $p = 0.195$; i.e., the performance was reduced, but the difference between proportions was not significant.

We present the statistical analysis for completeness; however, generalization cannot be achieved by a single test subject. Further experiments with more test subjects are required to truly understand the effects of haptic communication training.

V. Discussion

The results of our demonstration clearly indicate that commanding our test subject to perform multiple tasks via vibrotactile cues was successful. For a single command, the test subject's sensitivity to the haptic command was high, only slightly shy of its sensitivity to the vocal command. Target behaviors were reliably executed for the "spin" command, with only one out of 18 commands missed- this is in fact a higher execution rate that of vocal commands, where 3 out of 18 were missed. Furthering the ability to understand a single haptic command, we show that our test subject can discern between different types of haptic cues. It is evident that the pronged motor housings successfully deliver haptic cues to non-bony areas of the dog. Furthermore, the signal perception threshold was lower compared to previously used vibrotactile delivery methods. Furthermore, our demonstration shows that commands do not have to rely on spatial 'hints' (i.e., when a vibration is felt on the right side, turn right).

Non-vocal communication may prove beneficial in many cases, such as discrete contact with MWDs, increasing capabilities of SAR and other working dogs, reconnecting with run-away pets, communication by speech-impaired handlers, and even communicating with deaf dogs. Our current proof-of-concept study shows promising results that open the way towards the use of haptics for human-canine communication. Our device may also be used to work with existing dog training devices, such as those using posture detection and automatized reward systems. Integrating different devices may advance the development of fully or partially autonomic dog training by assessing behavior, commanding, assessing response, and rewarding dogs for proper behavior.

Further research is needed test the validity, reliability, reproducibility and generalizability of our results. Our future research will focus on testing haptic training on a greater number of dogs of different breeds, ages and training histories. Furthermore, additional design parameters may be tested, including the amount and location of vibration motors, vibration amplitude range, motor synchronizations, vibration frequency, signal waveform etc. The integration of such a device into existing dog training programs such as SAR, MWD, and service dogs should be investigated as well.

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