FIDO—Facilitating interactions for dogs with occupations: wearable communication interfaces for working dogs

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Abstract Working dogs have improved the lives of thousands of people throughout history. However, communication between human and canine partners is currently limited. The main goal of the FIDO project is to research fundamental aspects of wearable technologies to support communication between working dogs and their handlers. In this study, the FIDO team investigated on-body interfaces for dogs in the form of wearable technology integrated into assistance dog vests. We created five different sensors that dogs could activate based on natural dog behaviors such as biting, tugging, and nose touches. We then tested the sensors on-body with eight dogs previously trained for a variety of occupations and compared their effectiveness in several dimensions. We were able to demonstrate that it is possible to create wearable sensors that dogs can reliably activate on command, and to determine cognitive and physical factors that affect dogs' success with body–worn interaction technology.

Keywords Wearable technology · Animal–computer interaction · Assistance dogs

1 Introduction

Ashley, who has epilepsy, is standing in line at a coffee shop when she starts to feel disoriented. Her medical alert dog, Roman, senses her oncoming seizure and begins nudging her back toward a wall. As Ashley sinks to the floor, Roman bites a small cylinder hanging from his service dog vest, activating Ashley's cell phone to call 911 and text her husband with their location. As Ashley loses consciousness, Roman licks her face, waiting for help that is already on the way.

Charles is engrossed in a movie in his dark home theater when his hearing service dog, Schubert, alerts. "What is it, Schubert, the doorbell?" Charles signs, and Schubert touches one of the four buttons on his vest with his nose. A message appears on Charles' head-mounted display. "Tornado siren? Oh my!" As they immediately head to the basement, Charles praises Schubert for the warning that may have saved their lives.

Police sergeant Sarah Gray knows that time is of the essence as she gives a hand signal to her Search and Rescue dog, Stryker. Stryker begins a sweep of the woods off to his right; he picks up a familiar scent and follows it, running faster as it gets stronger. In a small hollow, he locates his target: the 6-year-old child who wandered away from her family's campsite. He tugs a cord attached to his vest, which activates a wearable GPS communicator, geolocating and transmitting his position to his handler and a medical team standing by. A tone tells Stryker that his work is done, and he lies down near the little girl, waiting for his handler and her team to arrive.

The scenarios above are just a sampling of the many ways dogs could use wearable electronics to communicate with humans. Dogs currently work in varied domains: guide dogs serve people with visual impairments [6, 19]; service dogs aid people with physical disabilities [2]; hearing dogs alert people with auditory disabilities to sounds [2]; search and rescue dogs can locate people who are lost. These highly trained canines perform critical, even life-saving tasks.

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The main goal of the FIDO project is to research fundamental aspects of wearable technologies to support communication from working dogs to their handlers. We integrated electronics into dog clothing to create canine user interfaces and performed a pilot study of four different sensors [8]. From the results of the pilot study, we created five new wearable sensor designs. This paper summarizes the pilot study and details the results of testing the new designs with eight trained dogs. We evaluated and compared the sensors with a variety of metrics, including training time, ease of interaction, error rate, and false-positive rate.

2 Background and related work

Although animals have operated machines since the time of Skinner [18], Animal-Computer Interfaces (ACI) are relatively new. Recently, there has been interesting work on "interspecies interaction," including games, remote monitoring, and remote interaction. Games such as "Cat Cat Revolution" [12] and "Feline Fun Park" [23] allow humans to play with cats mediated by computing. The "Canine Amusement and Training" (CAT) system focuses on games as a way to teach humans to train and interact with dogs [22]. Remote interaction systems allow a human to monitor, care for, and play with their pets at home when they are away [7, 9, 11, 16]. Dog-mounted GPS and video cameras can give their owners a perspective on the dog's experiences in the household [10] and hunters a better view of their working dogs' activities [13, 21]. Researchers have trained an assistance dog to take commands from a speaker worn on his body [17]. While some of these studies support handler-to-dog communication or monitoring, they have not yet explored dog-to-handler interactions.

3 Pilot study

We first performed a pilot study [8] to determine the types of sensors dogs can most easily understand and activate. We based four different sensor designs on natural capabilities of dogs—biting, tugging, and touching with the nose. Because dogs naturally explore their environment predominantly with their noses and mouths, we opted to design sensors for nose and mouth interaction rather than paws or other body parts.

3.1 Pilot study sensors

We created two bite sensors with different form factors, one proximity (gesture) sensor and one tug sensor. Assistance dogs are trained to interact with a variety of materials, from fabrics to metals, but we attempted to design sensors with materials that were as close as possible to dog toys for appeal and comfort.

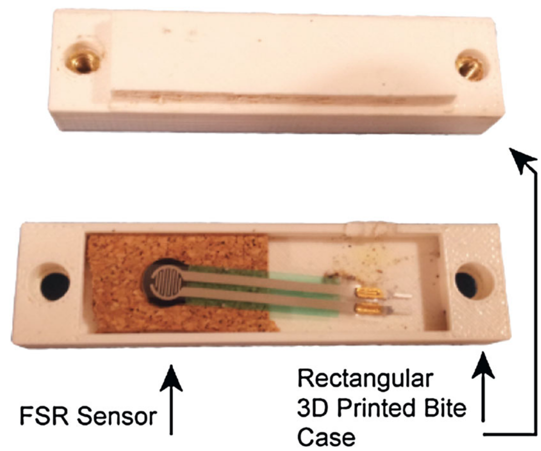

Fig. 1 Rectangular case for FSR sensor

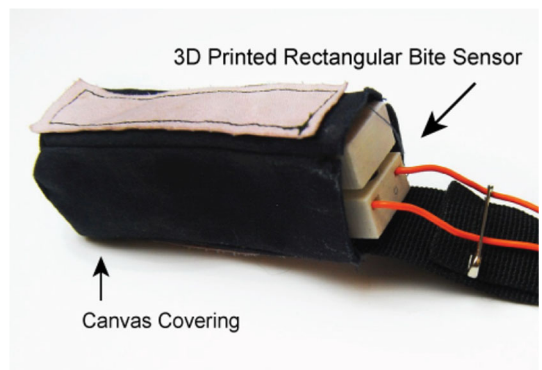

Fig. 2 Rectangular bite sensor with fabric cover

3.1.1 Pilot study bite sensors

We used force-sensitive resistors (FSRs) [4] and a 3D-printed enclosure to construct two different shaped bite sensors: an oval and a rectangle. Each bite sensor had a 0.16″ (4 mm) diameter active sensing area and varied its resistance depending on how much pressure was applied to the sensing area. The harder the force, the lower the resistance. Crossing a predetermined force threshold activated the sensor.

Rectangular bite sensor The motivation for the rectangular bite sensor was to simulate the form factor of a "bringsel," which is a padded stick attached to the collar of a Search and Rescue (SAR) dog. When a SAR dog finds its target, it holds the bringsel in its mouth and returns to the handler. To achieve this, the bite sensor (Fig. 1) was covered in nylon fabric with two pieces of colored fabric identifying the top and bottom (Fig. 2).

We attached the sensors on the left side of a dog vest, using nylon straps linked to a metal ring on the vest (Fig. 3). All sensors were placed in a manner similar to that illustrated in the figure. We chose this location because it

Fig. 3 Retriever with vest and rectangular sensor on left side configuration

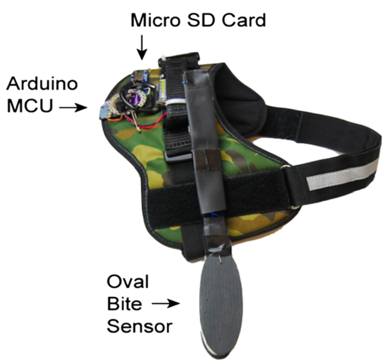

Fig. 4 Oval bite sensor with microprocessor on vest

would be accessible to a wide range of dogs, per the recommendation of our dog training experts.

Oval bite sensor The oval form factor for the FSR case was internally similar to the rectangular version; the difference lay in the external appearance. In this case, the bitable surface area was larger in order to ensure that the dogs bit the sensor perpendicularly to its surface rather than in a parallel fashion. In order to make the casing more inviting for biting, it was covered in black rubber material to simulate a dog toy as shown in Fig. 4.

The dogs activated the bite sensors by reaching to grasp the sensor, as shown in Fig. 5.

3.1.2 Ultrasonic proximity sensor

Our proximity sensor utilized an ultrasonic range finder with an analog output, set to detect movement at a distance of <3 cm. A small conical shield around the sensor protected it from activating too easily from objects in the

Fig. 5 Retriever activating oval bite sensor on-body

Fig. 6 Proximity sensor on dog vest

environment, as shown in Fig. 6. The dog placed its nose directly over the sensor to activate it.

The proximity sensor was wired to one of the analog pins on the microcontroller to capture the sensor values as objects moved toward and away from the sensor. In order to detect object distance, the microcontroller implemented a moving average of fifty readings and produced a beeping sound if that average was lower or equal to the preset threshold. The buzzer would beep if an object was in front of the sensor for half of a second and turned off once the object moved away approximately 18 cm.

3.1.3 Tug sensor

The tug sensor consisted of a 10-cm stretchable rubber variable resistor sewn into an elastic band, which was in

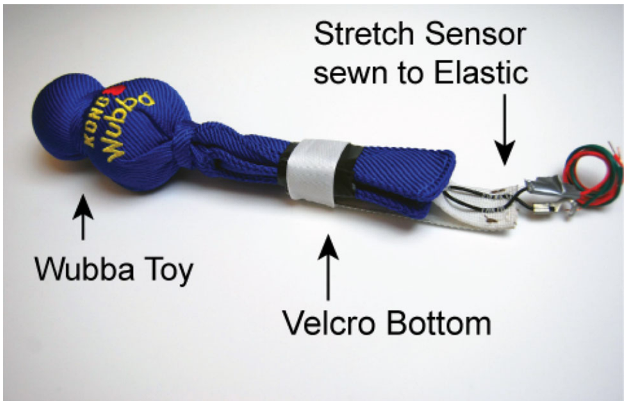

Fig. 7 Tug sensor showing variable resistor sewn into elastic

Fig. 8 Border collie activating tug sensor on-body

turn sewn to a small commercial dog toy (Kong "Wubba") as shown in Fig. 7. The dog activated the sensor by grasping and tugging the toy with his teeth. The sensor detected the force of a dog pulling on it and, like the previous sensors, triggered a beeping to sound if the force applied exceeded a threshold.

The tug sensor was designed to be strong enough to compensate for the fragility of the stretch-sensing resistor, yet sensitive enough to register a tug by the dog's mouth. This compromise was achieved by sewing the resistor into an equal length of elastic. Because the elastic was not as stretchable as the resistor and was also much more durable in terms of withstanding pulling force, it enabled the tug sensor to stretch enough to change its resistance, but not enough to break it as the dog pulled on it. This apparatus was mounted on the side of the dog's vest in a horizontal orientation. To activate the tug sensor, the dogs reached around and grasped the ball of the dog toy, gave a brief tug, and released, as shown in Fig. 8.

Table 1 Pilot study overall success for each sensor

Dog	Bite oval	Bite rectangle	Tug	Proximity
BC1 (%)	87	70	36	86
BC2 (%)	92	70	45	90
R1 (%)	30	0	100	42
Avg (%)	70	47	60	73

3.2 Pilot study results summary

The details of our metrics for both the pilot study and the follow-on study are described in Sect. 5 (Results) below. The full results of the pilot study are presented in Jackson et al. [8], but we will summarize here. Table 1 details the overall success of each sensor, which is the percentage of handler commands that resulted in a sensor activation.

The overall success metric showed that the proximity sensor and the oval bite sensor were the most effective sensors in our testing scenario. In terms of dog accuracy, which measures dog understanding of how to activate the sensor, the rectangle bite sensor was the best. This result could be attributed to the fact that all of the dogs were previously trained to retrieve, so biting and holding an object were a natural interaction for them. In terms of sensor accuracy (i.e., when the dogs attempted to activate the sensor properly, the action registered as intended), the proximity sensor was highly reliable. However, it also exhibited the greatest number of false positives. This increased rate illustrates a predictable trade-off between accidental activation and ease of activation. Similarly, the oval bite sensor data show a trade-off between reachability and ease of activation. The longer the sensor hung from the vest, the easier it was to reach, while also becoming more susceptible to the dog lying on it. Previous training had a profound effect on the bite sensor results. Service dogs that had been trained to perform a precision retrieve (such as picking up dropped objects or pulling off their handler's socks) often did not bite hard enough to activate the sensors. The agility-trained dogs had much more success with their more vigorous bite. However, the service dog's (R1) precision retrieve was an advantage on the tug sensor, with 100 % overall accuracy. His steady, controlled tugging action produced the best results. Dogs with more vigorous tug training tended to accidentally activate the sensor multiple times, which was penalized by our accuracy metrics. To improve the tug sensor, a more robust and flexible design that could be calibrated for the dogs' tug strength would improve performance.

3.3 Pilot study sensor improvements

Calibration An important difference among our three pilot test dogs was bite and pull strength. For example, the two border collies had no problems with the bite sensor, whereas the retriever's softer mouth initially did not bite hard enough to pass the threshold, although he was otherwise performing a correct bite. An automated calibration of bite and tug force could help to adjust the sensitivity appropriate to the dog.

Proximity sensor improvements The proximity sensor could be improved by adding an adjustable range to customize its sensitivity for the dog and the environment. Alternatively, an infrared alternative might reduce triggers from inanimate objects. We also could position the sensor in a different area, such as under the neck, which would make it less vulnerable to triggering on objects such as doorways.

Sensor locations Anatomical differences are an important facet in designing sensors for dogs. Border collies are very flexible and can reach almost anywhere on their bodies. Retrievers and other larger dogs, however, are thicker through the neck and torso and may not be able to easily reach items that are close to their heads. Therefore, the sensors need to be reachable by the target dog breed. Further studies should include placing each sensor in different locations on the dog vest, or on a coat or sleeve.

4 Methods: follow-on study

Our eventual goal is to support multiple sensors on the dogs' vests to communicate a variety of messages. However, for consistency in the pilot study as well as the follow-on study, we tested each sensor individually in the same location on the left ribcage area of the dogs' vests. For each sensor, we measured the sensor readings during a series of dog interactions, as well as during normal assistance dog activities (to test for false activations). We then calculated performance metrics for both the dogs and the sensors.

4.1 Dog training method

Our two dog handlers are both very experienced animal trainers. The first (author Jackson) has been training dogs and horses for over 40 years; she has raised and trained assistance dogs for Canine Companions for Independence for the last 20 years and is now also competing at national levels in dog agility. The second trainer (author Currier) also has extensive experience with dogs and horses and is currently a professional dog agility trainer with over 18 years working in dog obedience, behavior modification, and agility. The two handlers worked together in testing all of the dogs for consistency.

For both the pilot and the follow-on studies, we selected dog subjects trained in certain skills: hand-target (touch the handler's hand with the nose), retrieve (grasp an object and bite down gently), and tugging (grasp an object and pull). All of the dogs had already been trained with operant conditioning techniques [18], specifically *shaping*, which is building new behaviors by selectively reinforcing behaviors the dog offers [11, 15]. For these experiments, we only used positive reinforcement; we did not employ correction or punishment. Positive reinforcement has been shown to increase the likelihood of dogs offering novel behaviors, which is important when training a dog for a task he has never performed before. Punishment or correction can discourage a dog from offering new behaviors [18].

Fig. 9 Pit bull learning sensor activation off-body

Initially, we classically conditioned [14] the dogs with high-value reinforcement (food) to a *reward marker,* a clicker. By marking desired behaviors with the clicker at the moment of execution, we shaped the dogs toward the final interaction goal for each sensor. Because each sensor produced a tone when activated, the dogs learned during training that the tone was the true reward marker, and they would work very hard to produce it.

All of the dogs we tested were already familiar with "tug" and "get it" (retrieve) commands. In order to start training the dogs with a familiar task, we started each dog with off-body interactions with each sensor. The handler presented the sensor to the dog and verbally encouraged him to interact with it, as shown in Fig. 9. When the dog offered an appropriate behavior (for example, taking a bite sensor in his mouth), the behavior was marked and the dog received a reward. Next, the dog was required to bite harder on the sensor to receive a treat, until the sensor was activated. All of the dogs learned to operate each sensor in a matter of minutes with this method.

Table 2 Subject demographics

Dog	Breed	Training	Sex	Age	Weight
BC1	Border collie	Assistance, Agility, FIDO	M	5	47 lbs (21.3 kg)
BC2	Border collie	Assistance, Agility, FIDO	M	4	33 lbs (15 kg)
BC3	Border collie	Agility	M	7	40 lbs (18 kg)
BC4	Border collie	Agility	M intact	16 mos	33 lbs (15 kg)
BC5	Border collie	Agility	M	3	32 lbs (14.5 kg)
R1	Retriever cross	Assistance, limited FIDO	M	5	72 lbs (32.6 kg)
R2	Retriever cross	Assistance, FIDO	M	5	70 lbs (31.7 kg)
PB1	Pit bull	Agility	M	5	49 lbs (22.2 kg)

Once the dog learned to operate each sensor off-body, we put the vest on the dog and began training with on-body activations. Through a series of hand-targets, we taught the dogs to find and activate the sensors on their bodies. Most dogs were proficient with each sensor after one training session; only one dog needed more initial training on the first sensor. The five sensors were presented to the test dogs in a pseudorandom order to lessen the effects of learning curves with the activation behaviors. Training and testing sessions were no more than 15 min, and no more than four sessions were held throughout a day with at least 30 min rest in between.

4.2 Subjects

As summarized in Table 2, we tested the sensors with eight dogs. Each dog's owner read and signed consent forms for both Institutional Review Board (IRB) and Institutional Animal Care and Use Committee (IACUC) for this study. We then collected demographic information for each dog including breed, previous training, sex, age, and weight. Our rationale for selecting these data is as follows. Different breeds could have different physical capabilities depending on structure. Previous training was important to gauge if any remedial training would be needed before introducing the FIDO sensors. All of the eight dogs were male for consistency of comparison; all were neutered except one ("intact"). We noted this because sometimes intact males can have higher drive than neutered males. Age of a dog can determine amount of training time as well as emotional and mental maturity [3]. Weight could determine the ability of a dog to be flexible; larger, heavier dogs might have a more difficult time bending to reach objects attached to their bodies than smaller, lighter dogs.

We interviewed the dogs' owners concerning each dog's background. BC1 is a border collie, raised with assistance dog training but currently working as a competition agility dog. BC1 has extensive experience with shaping techniques, tugging, and retrieving. BC2 is a border collie who is an active assistance dog. BC2 also has competition agility training and is very familiar with shaping, tugging, and retrieving. BC1 and BC2 participated in both the pilot and the follow-on studies. BC3 is a border collie trained in obedience and actively competing in agility. BC4 is a young border collie still in training for agility, with no competition experience. BC5 is a border collie also actively competing in agility. BC3, BC4, and BC5 had no previous FIDO training. R1 is a golden/lab cross-retriever. He was trained as an assistance dog, but is now a certified therapy dog. R1 had some limited previous FIDO training. R2 is also golden/lab cross-retriever. He is an active service dog trained with traditional techniques. He is familiar with shaping, but is trained for precision tugging and retrieving, which means he tugs very carefully (for tasks such as removing his handler's socks) and retrieves with a very soft bite. He also participated in both the pilot and the follow-on study. PB1 is a Pit bull trained for and actively competing in agility, with no previous FIDO experience.

4.3 Sensors

We tested the sensors with the Arduino UNO microcontrollers [1] based on the 8-bit Atmel AVR architecture. The sensors with analog outputs were connected to the analog input pins in the microcontroller and converted to a 10-bit digital value. All sensors had a predetermined threshold value, that once achieved or surpassed, indicated an activation. We determined the threshold for each sensor by trial and error during training; but once set, the threshold for each sensor was consistent for all dogs we tested. Successful activations were marked for both dogs and handlers by a tone from a small piezoelectric buzzer. On every loop-cycle, the sensor reading was recorded and stored externally for post-processing on a micro secure digital (SD) card. The sampling frequency depended on the instructions for the individual sensor. Based on SD card timestamps, we estimate the sampling frequency at once every 120 ms. We did not perform any filtering. As in the pilot study, we attached each sensor individually on the left ribcage area of a typical service dog vest. The dogs activated each sensor by reaching around to the sensor, performing a quick action (tug, bite, nose gesture), and then facing forward again.

4.3.1 Revised tug sensor

In the pilot study, the tug sensor was attached to a dog toy, which made it very intuitive for the dogs to find and

Fig. 10 Braided fleece tug sensor affordance

correctly interact with. However, the sensor did not consistently activate. This result could have been due to an activation threshold that was set too high, or problems with the placement of the sensor. The tug affordance was mounted in a sleeve that allowed it to be pulled forward, but it often snagged, preventing it from retracting to the non-activated position. In our next iteration of the tug sensor, we adjusted the angle and attachment point of the tug apparatus and also changed the material to give the dogs a better grip.

The revised tug sensor was based on an Images Scientific 4″ (10 cm) stretchable resistor sewn into an elastic band, which was in turn sewn to custom-made braided fleece "ball" affordance, as shown in Fig. 10. Assistance dogs are often trained to pull a braided fleece rope to open doors, refrigerators, and other items, so they are typically comfortable with the material.

As in the pilot version of the tug sensor, we sewed the stretchable variable resistor into an equal length of elastic. Because the elastic could not stretch as much as the resistor and was also much more durable in terms of withstanding pulling force, this approach enabled the pull sensor to stretch enough to change its resistance but not enough to break it as the dog pulled on it. We attached the tug sensor farther back on the vest than in the pilot study, and in a diagonal angle rather than the horizontal angle of the pilot tug sensor. Figure 11 illustrates the construction of the revised tug sensor system, showing the new angle of attachment and the braided fleece affordance.

To activate the revised tug sensor, the dogs reached around and grasped the ball-like affordance, gave a brief tug, and released, as shown in Fig. 12.

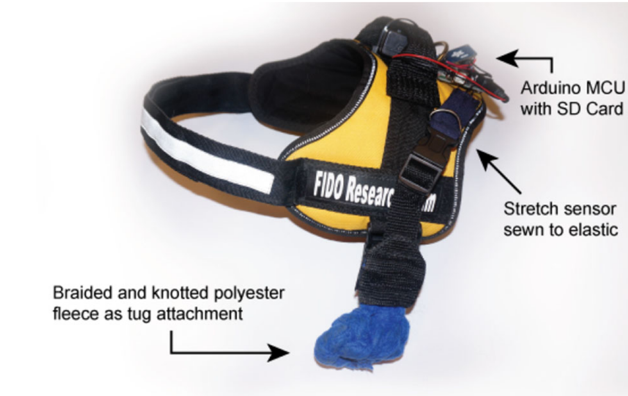

Fig. 11 Revised tug sensor on vest

Fig. 12 Border collie activating revised tug sensor on-body

4.3.2 *Infrared proximity sensor*

The proximity sensor in our pilot study was ultrasonic, and while it was one of the best performers for ease of activation, its false-positive rate was higher than any other sensor. For the follow-on study, we chose to re-implement this sensor using an infrared approach instead. Our revised proximity sensor was based on the VCNL 4000 infrared module [20], shown in Fig. 13. It was set to detect movement at a distance of less than 2 cm.

This module produced readings via a digital output specified by the SPI-protocol. The VCNL 4000 breakout board was wired to the SPI pins on the microcontroller to capture the sensor values as objects moved toward and away from the sensor. The proximity sensor was mounted on the side of the vest, near to the front, as shown in Fig. 14.

The dog placed his nose directly over the sensor to activate it; he did not need to touch it. Activating this sensor was a bit more abstract for the dogs, since there was no obvious affordance to interact with; they simply had to perform the movement without biting or tugging. Figure 15 shows a dog activating the infrared proximity sensor with a nose gesture.

4.3.3 *Bite sensors*

Our preliminary experiments illuminated two main areas of improvement for the bite sensors. The first and most

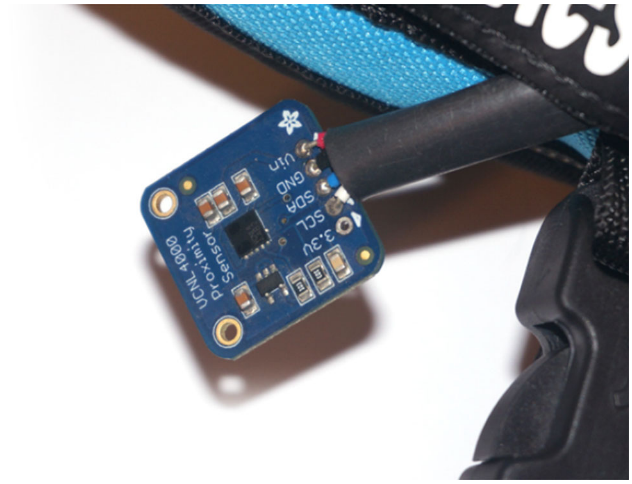

Fig. 13 Infrared proximity sensor

Fig. 14 Infrared proximity sensor on vest

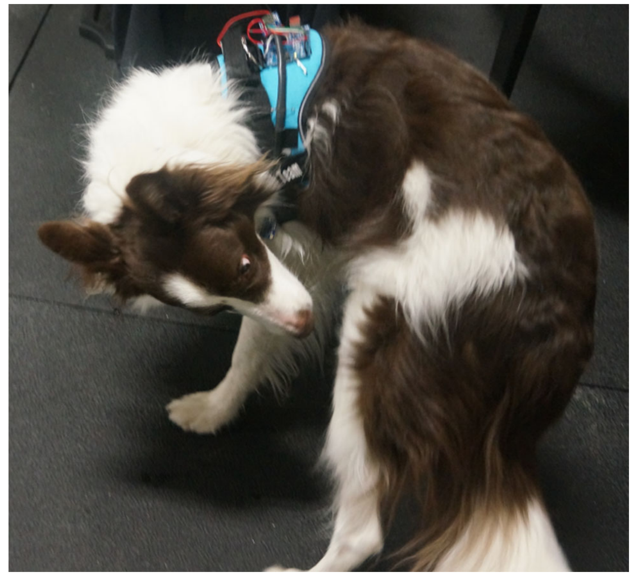

Fig. 15 Border collie activating the infrared proximity sensor

important involved the directionality of the biting action. In both the oval and rectangular bite sensors, due to the flat nature of the underlying FSR, and the case covering it, pressure had to be applied perpendicular to the surface. The rectangular sensor casing did not suggest that one direction was preferred over the other, and as a result, dogs tended to bite it in both directions (only one direction would activate the sensor). The oval sensor had better affordances for bite direction, but when the dogs attempted to activate the sensor, they sometimes grasped it with an imperfectly aligned bite. The dogs quickly learned to shift the sensor in their mouths, but activation was much less efficient. In our follow-on study, we developed a multi-sided bite sensor that can be activated from several angles to address this issue.

Second, when biting the sensor cases, the dogs tended to look for an "anchor point" to allow for a stronger grasp. On the rectangular sensor, this anchor point was the screw holes along the top of the case. Unfortunately, biting the screws transfers the force directly to the other side of the sensor, bypassing the FSR, and decreasing the sensor accuracy. We took this into consideration when designing the next iteration of bite sensors, relocating, and sometimes removing screws as fasteners. We created two new bite sensors, pneumatic and capacitive, to avoid these problems.

4.3.3.1 Four-sided bite sensor To mitigate the problems of our two-sided bite sensors from the pilot study, we used force-sensitive resistors (FSRs) [4] and a 3D-printed enclosure to construct a four-sided bite sensor. Each FSR was 0.16″ (4 mm) in diameter and had an active sensing area that varied its resistance depending on how much pressure was applied to the sensing area. The harder the force, the lower the resistance. When no pressure is applied to the FSR, its resistance will be larger than 1 MΩ; with full pressure applied, the resistance will be 2.5 kΩ. Four of these sensors were connected in parallel to achieve a four-sided bite sensor.

The motivation for this bite sensor was to alleviate the issues from the pilot bite sensors that required bite pressure to be applied in one particular direction. Additionally, it simulates the form factor of a "bringsel," similar to the rectangular bite sensor from the pilot study. The bite sensor (Fig. 16) was covered with small pieces of gaffer's tape to prevent the surface from becoming slippery when wet.

The inner portion of the bite panels, shown in Fig. 17, was curved along the shortest side in order to guarantee that the pressure would be distributed more evenly along the flat bed where the sensor lay.

Fig. 16 Four-sided bite sensor exterior

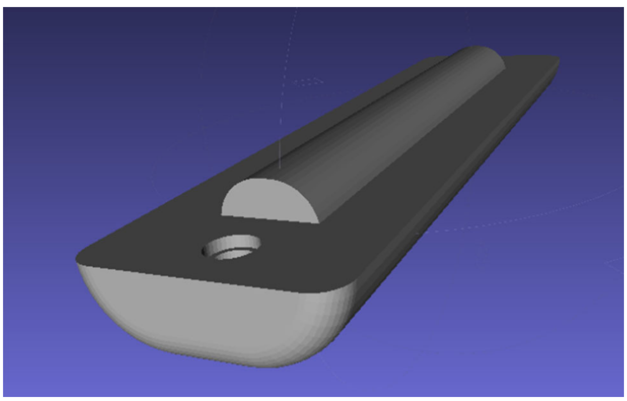

Fig. 17 Inner surface of bite panels for the four-sided bite sensor

To prevent movement of the internal wires, the connection between the FSR and wires was glued to the sensor bed as shown in Fig. 18.

Additionally, since the wire gauge was thicker than that of the sensor, the FSRs were elevated with a small piece of tape to avoid the pressure from falling on the wires.

The four-sided bite sensor was mounted on the vest in a similar manner to the tug sensor, toward the rear of the vest on a slight diagonal as shown in Fig. 19.

The dogs activated the sensor by reaching back and grasping the sensor along its narrower axis, shown in Fig. 20. Although a bite in either direction could activate the sensor, it was important that the dog orient the sensor correctly longitudinally. This orientation allowed the dog to press two of the panels simultaneously to activate the FSR.

4.3.3.2 Capacitive bite sensor In the pilot study, we observed that dogs with "softer" bites had more difficulty interacting with our bite and tug sensors. We wanted to create a sensor that did not require the dog to find the correct orientation of the sensor to activate it. We also desired to require less tugging or biting force for the lower-drive dogs. The goal was to create a sensor that would

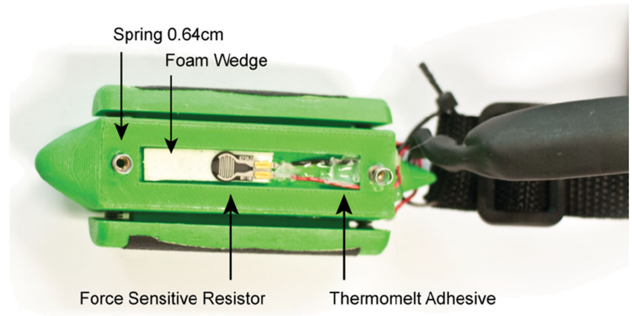

Fig. 18 Four-sided bite sensor interior

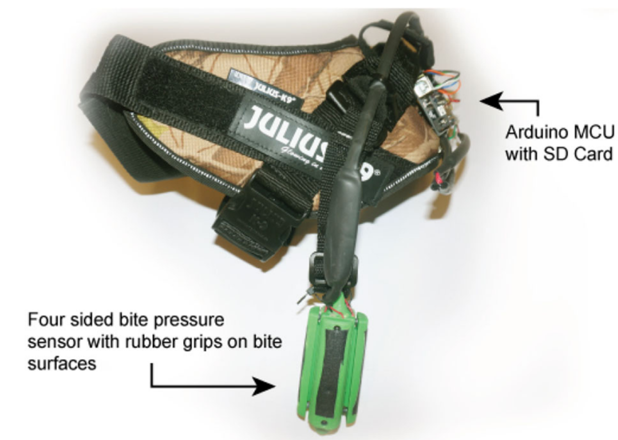

Fig. 19 Four-sided bite sensor mounted on vest

Fig. 20 Border collie activating the four-sided bite sensor

Fig. 21 Capacitive sensor in heat shrink tubing

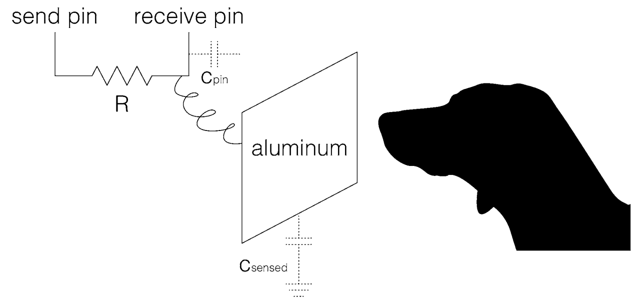

Fig. 22 Capacitive sensor operation

activate when a dog picked the sensor up in their mouth, but not when brushing against their fur or objects in the environment.

The capacitive sensor consisted of a length of PVC pipe, with four aluminum strips down the outside. Each strip was connected to a circuit that measured the capacitance of the metal strip. As shown in Fig. 21, the pipe and metal strips were then wrapped with heat shrink tubing that would provide both a rubbery surface that was easier for the dogs to grip in their mouths, as well as prevent them from coming in contact with the thin aluminum sensing components, which could damage the sensor.

When the dog grabs the sensor in his mouth, the moisture increases the capacitance of the metal strips under the heat shrink tubing, allowing us to detect when the sensor is picked up (Fig. 22). By using multiple strips, we reduced the accidental activations caused by brushing against either the dog's fur or other objects in the environment.

The capacitive sensor was mounted toward the rear of the vest, on a slight diagonal, similar to the placement of the four-sided sensor (Fig. 23).

To activate the capacitive sensor, the dog only needed to touch it with his mouth or even his nose. The direction of the grasp did not matter; in fact, the sensor could be activated by touching the wires above it. The dogs could easily reach around, lightly grasp the sensor, and activate it (Fig. 24).

4.3.3.3 Pneumatic bite sensor Another possibility for an omnidirectional bite sensor that does not require significant force is a pneumatic sensor (Fig. 25). The pneumatic sensor was modeled after a classic dog "chew toy." We embedded a barometer into a custom-made toy-like object that would activate when the dog lightly bit (compressed) it. This sensor was based on the Freescale MPL115A1 [5]. It works like a vehicle/traffic counter, which is a pressurized hose connected to a portable data collector. It detects a sudden rise in pressure at the ends of the tube when a car driving over it compresses the tube. For this sensor, the dog's bite performs the compression (Table 3).

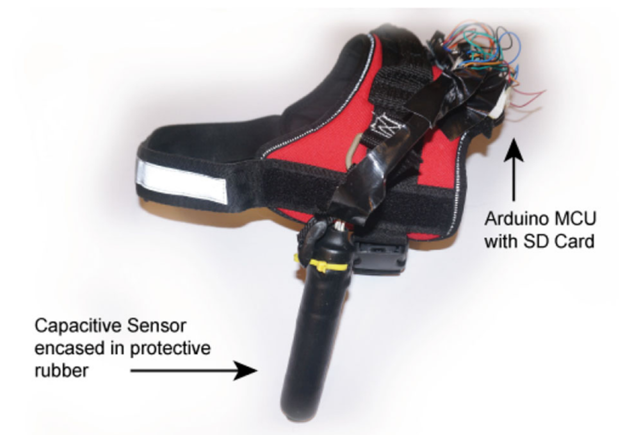

Fig. 23 Capacitive sensor mounted on vest

Fig. 24 Border collie activating capacitive sensor

Fig. 25 Pneumatic sensor from front (*top*) and from side (*bottom*)

The pneumatic bite sensor consisted of a digital barometer inside a sealed rubber tube. At one end, the barometer board was embedded in plastic to protect the circuit board from the dog's bite. This same piece of plastic also plugged the end of the tube, while the other end of the tube was sealed shut. A piece of foam inside the sensor helped to re-inflate it once it had been compressed. Figure 26 shows the configuration of the pneumatic sensor.

When a dog bites the sensor, the ends of the tube experience an increase in pressure greater than the set threshold, triggering a tone to give the dog feedback that he had successfully activated the sensor. Figure 27 shows a dog with a precision "soft bite" activating the pneumatic sensor.

Table 3 Training time

Dog	Tug	Prox	Four-sided bite	Capacitive bite	Pneumatic bite
BC1	1	2	3	4	5
Order, total, on, off	Previous training	Previous training	3:33	1:21	0:27
			3:33	1:21	0:27
			0	0	0
BC2	1	2	5	4	3
Order, total, on, off	Previous training	Previous training	0:47	0:40	1:12
			0:47	0:40	1:12
			0	0	0
BC3	1	5	4	2	3
Order, total, on, off	28:10	0:24	1:53	10:39	2:27
	15:16	0:24	1:12	9:11	2:27
	12:54	0	0:41	1:28	0
BC4	1	3	4	2	5
Order, total, on, off	6:15	2:35	0:51	1:08	0:22
	1:55	1:17	0:35	0:31	0:22
	4:17	1:18	0:16	0:37	0
BC5	3	5	4	1	2
Order, total, on, off	2:26	1:13	3:33	6:58	5:50
	2:26	0:48	0:28	5:31	3:16
	0	0:25	3:05	1:27	2:34
R1	2	5	4	1	3
Order, total, on, off	6:43	2:34	4:34	4:09	6:16
	4:00	2:34	4:34	2:21	6:16
	2:43	0	0	1:48	0
R2	1	2	3	5	4
Order, total, on, off	3:30	8:08	1:55	0:33	0:43
	3:30	8:08	1:55	0:33	0:43
	0	0	0	0	0
PB1	2	3	4	1	5
Order, total, on, off	2:47	6:30	0:54	4:46	0:30
	2:28	6:15	0:30	0:26	0:30
	0:19	0:15	0:24	4:20	0
Avg	8:18	3:34	2:15	3:47	2:13

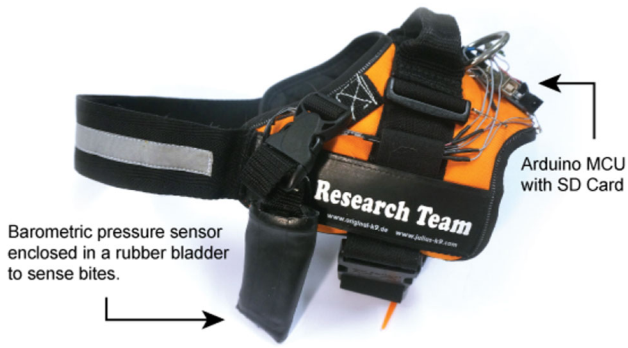

Fig. 26 Pneumatic sensor mounted on vest

Fig. 27 Retriever activating pneumatic sensor

4.4 Experimental protocol

Initial testing session Each dog participated in at least one training and one testing session for each sensor tested. All training and test sessions were videotaped for post-processing. After turning on the SD card recording data from the sensors, we performed a synchronization trigger (human activating the sensor) for time synchronization with the video. Training sessions began with off-body activations until the dog was comfortable with the interaction required. When the dog was proficient off-body, we put the vest on the dog and trained him to find and activate each sensor on his left ribcage area. When the dog was consistently operating the sensor on-body, we gave him a break and then moved on to the testing session. Each testing session consisted of the handler asking the dog to activate the sensor approximately ten times. After the corresponding attempts, the experiment concluded with another synchronization trigger. Both training and testing sessions were less than 5 min, some considerably shorter.

Normal activity session We performed 30-min false-positive tests for each sensor. Our test dogs wore vests with

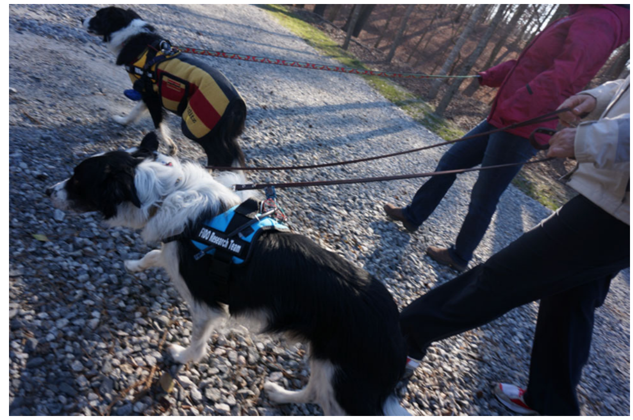

Fig. 28 False-positive testing

each sensor during normal assistance dog activities, walking outside on a hilly, forested path (Fig. 28). We videotaped the dogs and recorded the sensor values for the entire 30 min, with a sync trigger before and after the 30-min period to ensure the sensor was operating correctly. The dogs were allowed to perform normal behaviors, such as shaking and sniffing. The dogs were not asked to deliberately activate the sensors during the false-positive testing.

5 Results

To evaluate the sensors, we used several metrics, including training time, dog accuracy, sensor accuracy, sensor reachability, overall success, and false-positive rate. We describe each metric and then present a comparison of the five sensors.

5.1 Conventions

In analyzing the video data, we used the following conventions. Multiple commands from the handler for a single intent were counted as one (for instance, a verbal command paired with a gesture). We did not penalize unsuccessful activations from the vest slipping, or distractions external to the experiment. We slightly altered the angle of the proximity sensor for larger subjects (R1, R2, and PB1). We also lengthened or shortened the hanging sensors (tug, capacitive, pneumatic, four-sided bite) depending on the size of the dog. We counted multiple activations from one attempt (such as two beeps from a bite sensor while still in the dog's mouth) as one activation.

5.2 Activation graphs

To understand activation patterns for each sensor, we used time-based activation graphs similar to the ones in Figs. 29, 30, 31, 32 and 33.

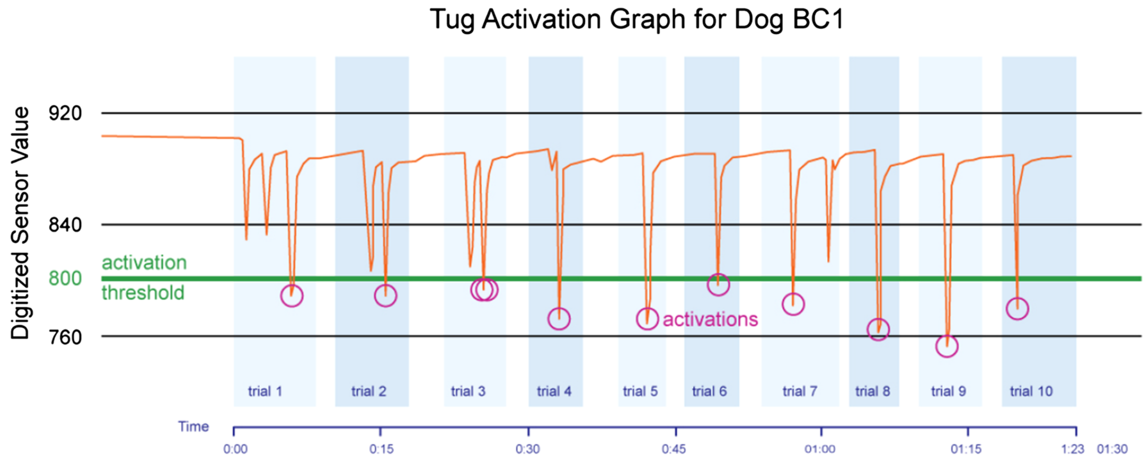

Fig. 29 Sample activation graph for tug sensor

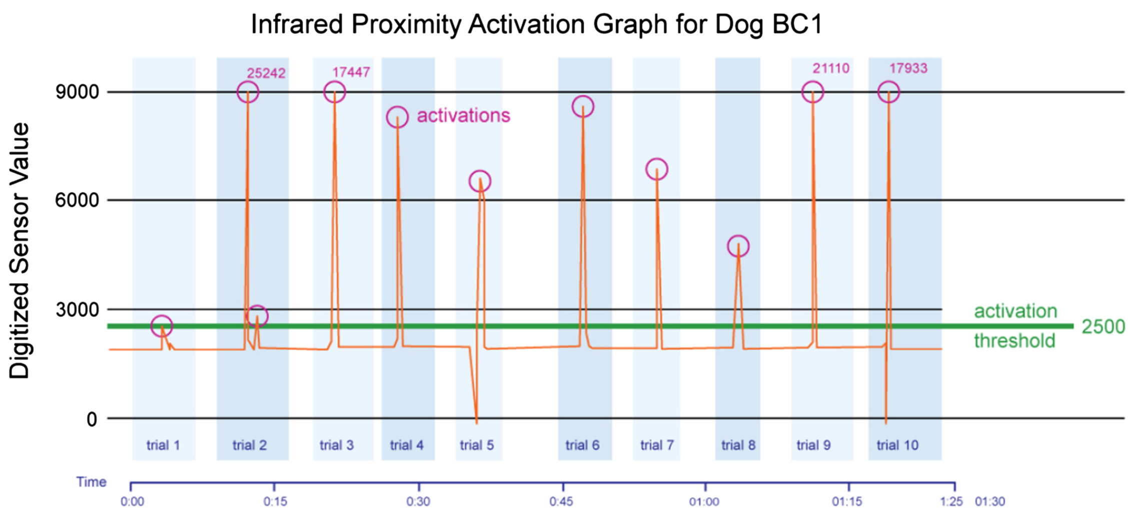

Fig. 30 Sample activation graph for the proximity sensor

Tug sensor The tug sensor activation pattern in Fig. 29 shows the value of the stretch sensor over the testing period. The threshold was determined empirically and is also shown as a green line.

Proximity sensor The proximity sensor's value corresponds to the distance of the nearest object, as shown in Fig. 30. As a result, the *y*-axis is inverted in comparison with the other sensors. Activations are indicated by the sensor value decreasing below the distance threshold (rather than exceeding it).

Four-sided pressure sensor The four-sided pressure sensor graph in Fig. 31 shows the threshold (in green) set at the halfway point on the pressure scale of the force-sensitive resistors.

Capacitive sensor The capacitive sensor contains four different sensors inside that can individually activate; if any two of the internal sensors exceeded the threshold, the entire sensor would activate (producing a tone). Figure 32 shows the capacitance values for all four internal sensors over the testing time, with the activation threshold shown as a green line. Peak values for each internal sensor are shown by small circles.

Pneumatic bite sensor The pneumatic bite sensor in Fig. 33 shows pressure readings from the barometer inside the tube, again with a threshold represented as a horizontal green line.

5.3 Training time

All videos were time-stamped, and in post-processing, we calculated the amount of time spent training each dog on each sensor. We did not count time calibrating the sensor or adjusting the vest to fit the dog as training time; we only counted time interacting with the dog. We counted both off-body and on-body time in training, as well as the order in which the sensors were presented to the dog.

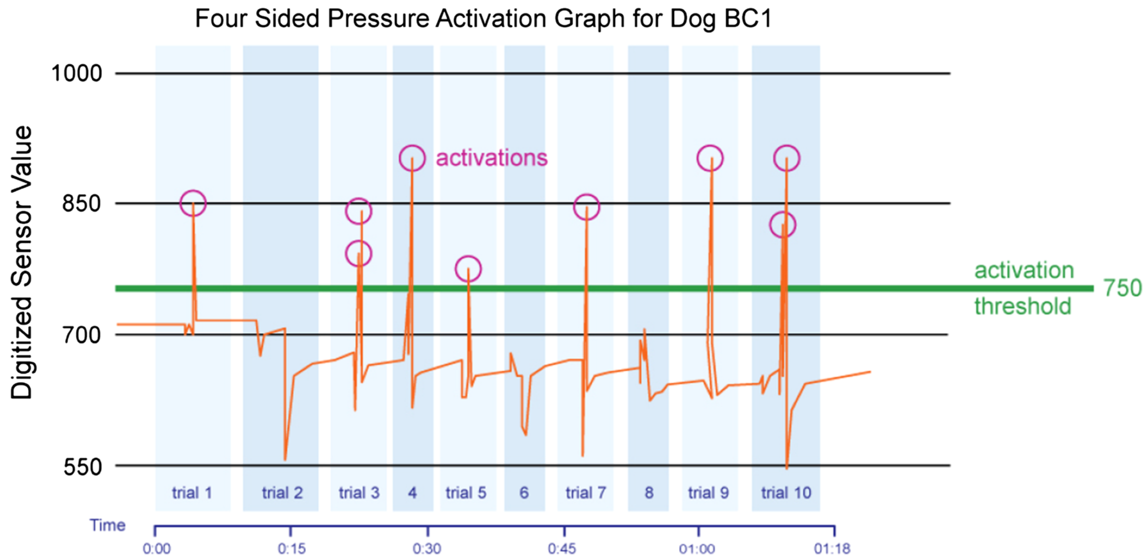

Fig. 31 Sample activation graph for the four-sided bite sensor

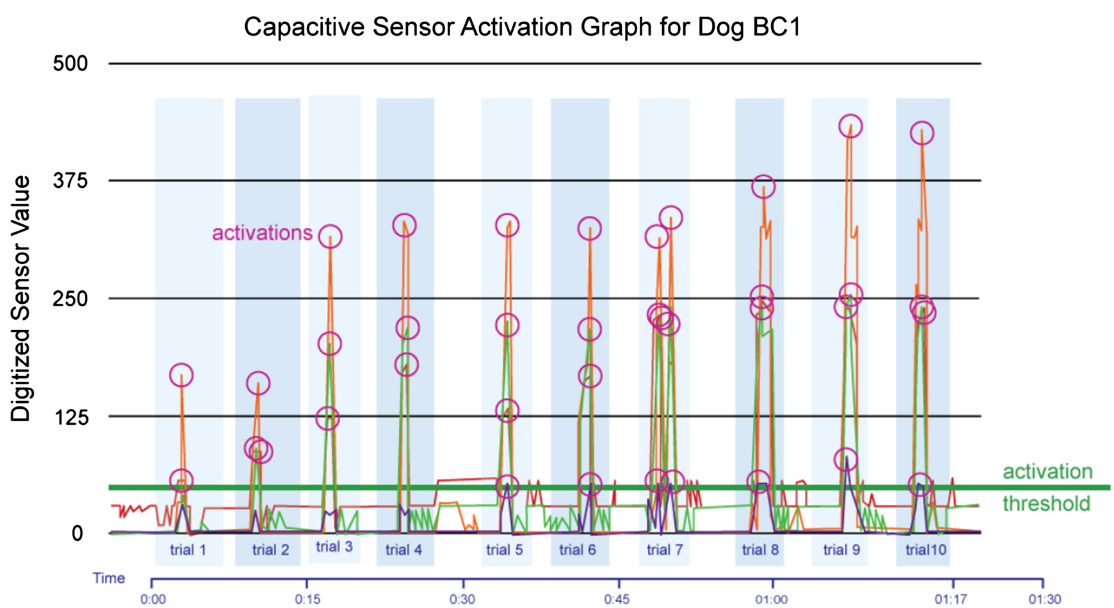

Fig. 32 Sample activation graph for the capacitive sensor

We varied the order of sensor training in order to measure learning effects.

5.4 Dog accuracy (DA)

We calculated accuracy for dogs as

$\mathrm{DA} = (N - D - S - I)/N \times 100,$

where $N =$ number of commands from handler to dog; $D =$ deletions, dog did not attempt to activate; $S =$ substitutions, dog performed wrong action; $I =$ insertions, dog activated without command.

This metric determines the subject's understanding of the sensor interaction task. It does not require sensor activation, only correct interaction with the sensor. Table 4 below summarizes the DA results:

5.5 Sensor accuracy (SA)

SA calculates accuracy of the sensor only. For this metric,

$\mathrm{SA} = (N - D - I)/N \times 100,$

where $N =$ correct attempts (bites, tugs) from the dog; $D =$ deletions, sensor did not activate; $I =$ insertions, sensor activated without interaction.

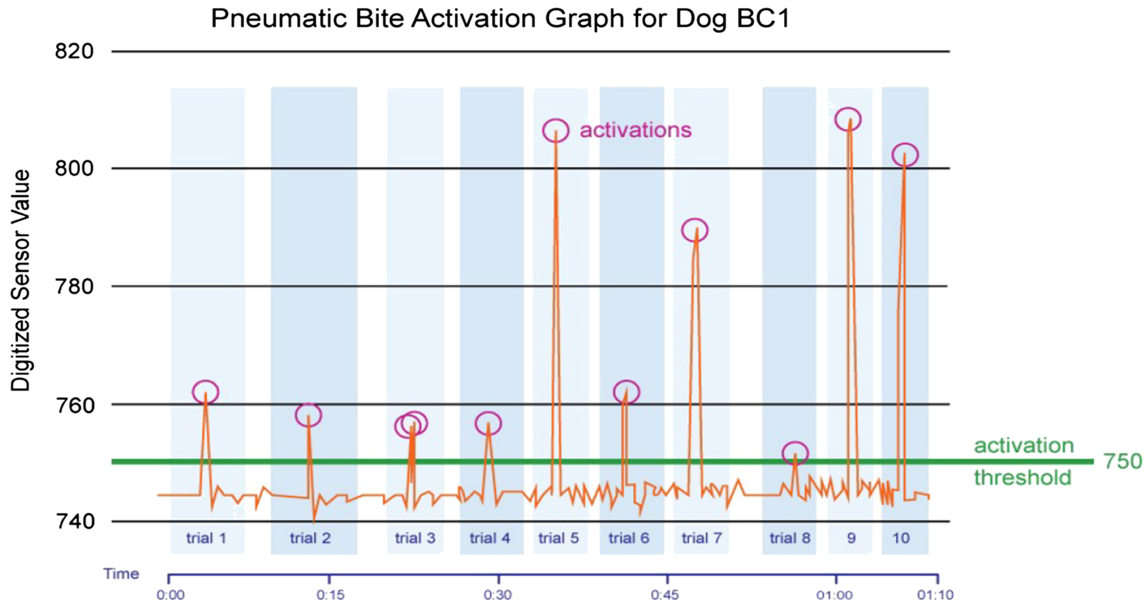

Fig. 33 Sample activation graph for the pneumatic bite sensor

Table 4 Dog accuracy for each sensor

Dog	Tug	Prox	Four-sided bite	Capacitive bite	Pneumatic bite
BC1 (%)	90	90	100	100	100
N, *D*, *S*, *I*	10, 0, 1, 0	10, 0, 1, 0	10, 0, 0, 0	10, 0, 0, 0	10, 0, 0, 0
BC2 (%)	60	60	100	100	100
N, *D*, *S*, *I*	10, 0, 3, 1	10, 0, 0, 4	10, 0, 0, 0	10, 0, 0, 0	10, 0, 0, 0
BC3 (%)	100	100	92	100	70
N, *D*, *S*, *I*	10, 0, 0, 0	10, 0, 0, 0	13, 0, 0, 1	10, 0, 0, 0	10, 0, 3, 0
BC4 (%)	90	100	83	100	100
N, *D*, *S*, *I*	10, 0, 0, 1	10, 0, 0, 0	12, 0, 2, 0	10, 0, 0, 0	10, 0, 0, 0
BC5 (%)	100	100	100	100	100
N, *D*, *S*, *I*	13, 0, 0, 0	10, 0, 0, 0	10, 0, 0, 0	10, 0, 0, 0	10, 0, 0, 0
R1 (%)	40	0	100	90	100
N, *D*, *S*, *I*	10, 6, 0, 0	10, 10, 0, 0	11, 0, 0, 0	10, 1, 0, 0	10, 0, 0, 0
R2 (%)	87	0	100	100	60
N, *D*, *S*, *I*	15, 2, 0, 0	10, 10, 0, 0	10, 0, 0, 0	10, 0, 0, 0	10, 0, 4, 0
PB1 (%)	100	0	100	90	100
N, *D*, *S*, *I*	10, 0, 0, 0	10, 10, 0, 0	10, 0, 0, 0	10, 0, 1, 0	10, 0, 0, 0
Avg (%)	83	56	97	98	91

Table 5 compares the SA of each sensor.

5.6 Sensor reachability (SR)

This metric quantifies the difficulty associated with reaching the sensor due to its placement on the body. It is calculated as

$\mathrm{SR} = A/N \times 100$,

where $N =$ number of attempts to access the device; $A =$ number of successful acquisitions (regardless of activation).

Perfect score for SR is 100 %. Values below 100 % indicate higher difficulty. Table 6 summarizes these results.

Table 5 Sensor accuracy for each sensor

Dog	Tug	Prox	Four-sided bite	Capacitive bite	Pneumatic bite
BC1 (%)	73	92	75	100	100
N, *D*, *I*	15, 4, 0	13, 1, 0	12, 3, 0	10, 0, 0	10, 0, 0
BC2 (%)	42	77	91	100	56
N, *D*, *I*	26, 15, 0	22, 5, 0	11, 1, 0	10, 0, 0	16, 7, 0
BC3 (%)	95	100	92	100	78
N, *D*, *I*	19, 1, 0	10, 0, 0	13, 0, 1	10, 0, 0	18, 4, 0
BC4 (%)	67	89	67	92	91
N, *D*, *I*	12, 4, 0	18, 2, 0	15, 5, 0	13, 0, 1	11, 1, 0
BC5 (%)	64	100	89	100	70
N, *D*, *I*	14, 5, 0	13, 0, 0	9, 1, 0	12, 0, 0	10, 3, 0
R1 (%)	0	100	64	100	100
N, *D*, *I*	4, 4, 0	10, 0, 0	11, 4, 0	11, 0, 0	9, 0, 0
R2 (%)	38	100	67	100	100
N, *D*, *I*	21, 13, 0	10, 0, 0	15, 5, 0	10, 0, 0	10, 0, 0
PB1 (%)	100	100	92	75	100
N, *D*, *I*	10, 0, 0	10, 0, 0	12, 1, 0	12, 0, 3	10, 0, 0
Avg (%)	60	95	80	96	87

Table 6 Sensor reachability for each sensor

Dog	Tug	Prox	Four-sided bite	Capacitive bite	Pneumatic bite
BC1 (%)	100	85	100	100	100
N, *A*	15, 15	13, 11	12, 12	10, 10	10, 10
BC2 (%)	100	45	91	100	100
N, *A*	26, 26	22, 12	11, 10	10, 10	16, 16
BC3 (%)	58	100	80	100	100
N, *A*	19, 11	10, 10	20, 4	10, 10	10, 10
BC4 (%)	100	78	73	100	100
N, *A*	12, 12	18, 4	15, 4	13, 13	11, 11
BC5 (%)	100	100	56	83	90
N, *A*	14, 14	13, 13	15, 9	12, 10	10, 9
R1 (%)	40	100	100	91	100
N, *A*	10, 4	10, 10	11, 11	11, 10	9, 9
R2 (%)	100	100	100	100	100
N, *A*	21, 21	10, 10	15, 15	10, 10	10, 10
PB1 (%)	100	100	92	92	100
N, *A*	10, 10	10, 10	12, 11	12, 11	10, 10
Avg (%)	87	89	87	96	99

5.7 Overall success (OS)

This metric quantifies how many commands resulted in successful activations. It is calculated as

$$\mathrm{OS} = A/N \times 100,$$

where $N =$ handler intents (commands); $A =$ successful activations.

Table 7 summarizes the results.

5.8 False-positive study

In order to quantify the false-positive vulnerability of each sensor, we conducted a "normal activity" field study of a dog wearing each vest during normal activity for a period of 30 min. We recorded each session on video and analyzed the video to attempt to determine the cause of the false activations. Table 8 summarizes these results.

Table 7 Overall success for each sensor

Dog	Tug	Prox	Four-sided bite	Capacitive bite	Pneumatic bite
BC1 (%)	100	100	70	100	100
A, *N*	10, 10	10, 10	7, 10	10, 10	10, 10
BC2 (%)	100	100	100	100	100
A, *N*	10, 10	10, 10	10, 10	10, 10	10, 10
BC3 (%)	100	100	77	100	100
A, *N*	10, 10	10, 10	10, 13	10, 10	10, 10
BC4 (%)	100	80	83	100	100
A, *N*	10, 10	8, 10	10, 12	10, 10	10, 10
BC5 (%)	69	100	90	100	100
A, *N*	9, 13	13, 13	9, 10	10, 10	10, 10
R1 (%)	0	0	64	100	100
A, *N*	0, 10	0, 10	7, 11	10, 10	10, 10
R2 (%)	100	0	100	100	100
A, *N*	10, 10	0, 10	10, 10	10, 10	10, 10
PB1 (%)	100	0	90	100	100
A, *N*	10, 10	0, 10	9, 10	10, 10	10, 10
Avg (%)	84	60	84	100	100

Most of the sensors performed very well in the false-positive testing. All of the bite sensors and the tug sensor had zero false positives. The proximity sensor activated accidentally five times because of the dog's leash.

6 Discussion

6.1 Sensor comparison

Overall success Our goal after the pilot study was to create bite sensors that did not depend on direction of bite. Clearly, we succeeded in achieving this, as both the capacitive sensor and the pneumatic sensor have 100 % overall success rates for all eight dogs (determining how many commands resulted in activations, a real-world usage metric). Indeed, these two bite sensors are among the best in all categories, which means they are easy for the dogs to find and reach, and easy for them to understand, as well as being easy to activate. These two sensors also had no false positives in our normal activity study. Therefore, they are our most successful sensors thus far. Clearly, these two bite sensors improved on the FSR-based bite sensors from the pilot study.

Sensor reachability We discovered that if the sensor attachment was too long, the dogs would tend to grasp the strap or wires that held the actual sensor (in the case of the capacitive sensor, this grasp did activate the sensor). If the sensor attachment was too short, the dogs had difficulty bending enough to reach it. The correct length for each sensor may be calculated from size measurements of the dogs; which also may determine how flexible the dogs are for bending.

Tug sensor changes In the pilot study, the tug sensor was one of the easiest and most reliable to activate. In the follow-on study, we changed the angle of attachment and included a different affordance. The tug sensor did not fare as well in this configuration, and in fact, one dog (R1) could not activate it at all. The dogs tended to spin when they tried to reach the sensor because it was too far back. The original design of the tug sensor, with its horizontal mount and dog-toy affordance, was more reliable for the dogs to activate.

Proximity sensor training The proximity sensor was difficult for some of the dogs to learn, as there is no obvious affordance to interact with. Interestingly, all five of the border collies quickly understood that a nose gesture would activate the sensor, but none of the non-border collie dogs were able to understand the gesture needed within one training session. Consequently, we opted to test the sensors with a hand target, which helped the dog find the correct position to activate the sensor. Although the dog may not have understood the gesture needed, he still activated the sensor with his nose. In the data analysis, we conservatively penalized the hand-target as a deletion (the dog did not understand how to activate the sensor independently). Consequently, all non-border collies have a dog accuracy (DA) score of 0 % for the proximity sensor. However, the sensor still achieves a sensor accuracy (SA) of 100 %. We have little doubt that all of the dogs could have learned to perform this gesture given more training time. However, with the proximity sensor's higher tendency to activate accidentally, the bite sensors are probably superior for real-world usage.

Table 8 Summary of false positives (FP) from normal activity study

Sensor	FP/30 min	Causes of FP
Tug	0	
Proximity	5	Leash touching
Four-sided bite	0	
Capacitive bite	0	
Pneumatic bite	0	

Capacitive sensor issues Although it was one of our most successful sensors, the capacitive sensor was not always intuitive for the dogs. They had no problem reaching or activating the sensor, but then, many of them would hold it in their mouths, causing it to activate constantly. The other sensors seemed to have a more clear "activate and release" paradigm for the dogs (possibly because of the force feedback from the tug and pneumatic sensors, as well as the four-sided bite sensor). The capacitive sensor had no "give," it was a static feel for the dogs, and we had to explicitly train the dogs to release it after activation.

Dog saliva effects All of the sensors became wet with repeated activations, but the capacitive, pneumatic, and proximity sensors were most susceptible to moisture effects. If the dogs actually touched or licked the proximity sensor, it would activate and stay activated until dried. A small protective cylinder or cone around the sensor (as we had employed in the pilot study) would prevent this from happening. Surprisingly, the capacitive sensor's performance was not affected by getting wet, other than becoming harder to grasp because it was slippery. The pneumatic sensor definitely was affected by becoming slippery; the dogs would attempt to grasp it and it would slide through their mouths. Often this activated the sensor, so it was not as large a factor in the success of this sensor as we might have expected. The tug sensor's braided fleece affordance was an advantage, as it was unaffected by getting wet.

Fragile four-sided bite The biggest issue with the four-sided bite sensor, which was 3D printed from plastic, was its fragility. It was held together by screws, and several times, the dogs managed to bite it in the right place to pop the panels off, spilling screws and springs. This situation could present a choking hazard for the dogs. One of the dogs had a powerful bite (PB1) and actually cracked the sensor when trying to activate it. The other sensors were much more robust to dog activations, so we concluded that printed plastic is not an acceptable material for a bite sensor in general.

6.2 Anatomical differences

The size and physical shape of the dogs largely determined how flexible they were and how easily they could reach their own ribcage area. Some notable anatomical differences made the sensors more of a challenge to some subjects: broad shoulders, thicker torsos, and shorter backs made activating the sensors more difficult. Border collies tend to be very flexible, so reaching their ribcage area was not difficult. Some of the larger dogs tried spinning, which flung the sensor outward with centrifugal force, making it easier to grasp. We also observed that dogs who were routinely stretched (agility dogs) were more flexible than dogs who were not. This observation might mean that dogs who are not naturally flexible could be helped to become more able to bend to reach things on their bodies by stretching exercises.

6.3 Dog training effects

We observed a clear learning curve in the training time calculations; in almost all dogs, training took less and less time as they worked through the five sensors. Once the dogs understood the interaction paradigm, they were able to generalize it. The most dramatic example is BC3, who took over 28 min to learn his first sensor. By the time he learned his fifth sensor, it only took 47 s for him to become proficient. Furthermore, his fifth sensor was the proximity sensor, which was "abstract" (no affordance to interact with) and arguably the most difficult to learn.

We discovered in the pilot study that dogs quickly learned that the tone was the actual marker for success, and they would continue to attempt to activate the sensor until they heard it, without commands from the handler. Our dog accuracy metrics penalized these extra attempts, but in overall accuracy, they were not penalized. In the follow-on study, we gave the dogs an intermediate task between activations (lie down or "watch" the handler) to teach them to only activate once. However, in real-world usage, the main task would be to communicate a message, and extra activations would most likely not be an issue.

All of the dogs were already trained to tug and retrieve before the experiment, so training the dogs on the bite and tug sensors was relatively easy. We observed an interesting learning progression with the dogs on the proximity sensor. All of the border collies discovered, on their own, that they only needed to wave their nose past the sensor, rather than trying to touch it or bite it. A few seconds into the training session, the dogs were clearly performing gestures with their noses, which was not a previously trained skill. Nose gestures could represent a straightforward method for extracting multiple signals from a single sensor (such as down to up, or up to down).

Subject R2 learned that spinning (a skill he was already trained to do) activated the proximity sensor. Even though this behavior was not optimal, it still resulted in a valid activation and was subsequently rewarded. In a real-usage scenario, we would take time to extinguish this behavior.

6.4 Sensor improvements

There are several aspects we could improve for the FIDO sensors. Making them more adjustable (length, placement on a vest) could be critical to success with different sized dogs, allowing us to test more breeds. Having a vest that fits the dog well is also critical; if the vests are too large, they slide around, making the sensors difficult or impossible to reach. To mitigate this problem, we are creating a sensor network that will allow us to "plug-and-play" different sensors on the same vest. This approach will allow us to have a variety of vest sizes to choose the one that fits the dog best.

7 Conclusions and future work

The results of the FIDO studies are extremely encouraging; we demonstrated that it is possible to create wearable electronics that dogs can reliably activate to communicate with their handlers. There is a vast amount of work yet to be done. The sensors need to be smaller, more robust and require less power. We plan to explore possible methods for multiple interactions with each sensor, which could increase communication bandwidth. We need to examine sensor placement bilaterally and beyond the ribcage area, to determine what locations are reachable by different dog body types, and to determine the optimal area for each sensor type. Along with the sensor placement study, we need to discover the best ways to train the dogs to differentiate multiple sensors on their bodies and to activate them on different environmental triggers. We plan to explore other sensors, such as "Touch-points," which are areas embroidered with conductive thread that could be activated with a simple nose or paw touch. We also plan to stress test the designs with dogs at speed on an obstacle course, which could simulate a rugged outdoor environment. This technology could easily be adapted to other canine professionals, for police work (bomb and drug sniffing dogs could report their finds) and military working dogs who could communicate the location and type of Improvised Explosive Devices (IEDs). Providing dogs with the ability to communicate clearly to humans opens a myriad of possibilities.

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