New Zealand Journal of Ecology (2023) 47(2): 3532

NEW ZEALAND JOURNAL OF ECOLOGY

RESEARCH

Suitability of radio telemetry for monitoring two New Zealand frogs (*Leiopelma archeyi* and *L. hamiltoni*)

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Published online: 31 August 2023

Abstract: The miniaturisation of very high frequency transmitters over the last 20 years has allowed researchers to use radio telemetry to study the movements and behaviours of increasingly smaller animals. However, the sensitive skin of many amphibians has continued to make fitting telemetry packages difficult. Here we describe the application of a waist-harness style radio telemetry package for use on two of New Zealand's native terrestrial frogs (*Leiopelma archeyi* and *L. hamiltoni*). To determine if the harness design was suitable for field use, we conducted a laboratory trial on four captive *L. hamiltoni*. Individuals carried harnesses for up to 22 consecutive days without abrasions or changes in behaviour. After confirming the harness would not negatively impact captive individuals, we fitted harnesses to 20 *L. hamiltoni* in Te Pākeka/Maud Island Scientific Reserve, northern South Island. We tracked individuals for a maximum of 8 days and recaptured *L. hamiltoni* showed no signs of skin irritation or skin damage at the time of harness removal. We also tested harnesses on four *L. archeyi* within the Wharekirauponga area of the Coromandel Forest Park, northeastern North Island. We were able to track one *L. archeyi* for 7 days before locating the transmitter loose in leaf litter. The harness detached from two additional individuals, one within 24 hours of frog release and another 12 hours after release. We were unable to relocate one individual. Although the use of radio telemetry on leiopelmatids is not without difficulties, the observations collected during our field trials provide strong support that a waist-harness design is a suitable and effective method to conduct short-term radio telemetry on leiopelmatid frogs.

Keywords: amphibian ecology, amphibian movement, amphibian tracking, frog tracking

Introduction

Due to the unique anatomy, complex life histories, and cryptic lifestyles of many amphibian species, locating and tracking individual amphibians can be challenging. However, the miniaturisation of very high frequency (VHF) transmitters over the last 20 years has allowed researchers to use radio telemetry to study the movements and behaviours of increasingly smaller amphibians (Jehle & Arntzen 2000; Indermaur et al. 2008; Ryan & Calhoun 2014; Lannoo et al. 2017; Pašukonis et al. 2019; Altobelli et al. 2022). Currently, the most frequently used method for attaching VHF transmitters to frogs is by using a waistband harness (Long et al. 2010; Altobelli et al. 2022). Externally attaching telemetry packages by a waistband harness is quick and minimally invasive allowing for the release of study subjects within minutes of capture which reduces handling stress (Bartelt & Peterson 2000; Guscio et al. 2008; Tatarian 2008; Pettit et al. 2017). However, waistband harnesses might not be suitable for all species of frogs as external attachment methods can increase energetic expenditure and lead to entanglement in vegetation (Germano 2006; Altobelli et al. 2022). Due to these risks, research into the impact of transmitter attachments on any new focal species are recommended when applying telemetry techniques (Rowley et al. 2007).

New Zealand has only three endemic species of amphibian, all frogs within the genus *Leiopelma* (*L. archeyi*, *L. hamiltoni*, and *L. hochstetteri*), and all are listed as Threatened or Vulnerable by the IUCN Red List (Bishop et al. 2013; IUCN 2021). Population declines in the two terrestrial species of New Zealand frogs (*L. archeyi* and *L. hamiltoni*) have been particularly pronounced (Bell 1994; Bishop et al. 2013). Further, a lack of knowledge surrounding basic movement patterns of these two species poses a particular challenge to our ability to manage their declines.

Leiopelma archeyi and *L. hamiltoni* represent two of the most evolutionary distinct and globally endangered species of amphibians in the world (Zoological Society of London 2021). Leiopelmatids diverged from all other frogs roughly 200 million years ago and possess many anatomical similarities to some of the earliest identified frogs within the fossil record (Roelants et al. 2007). Believed to reflect the basal state of frogs, Leiopelmatids serve as an important window into the evolutionary history of amphibians.

Currently, one of the leading strategies for native frog

DOI: https://doi.org/10.20417/nzjecol.47.3532

recovery in New Zealand is the use of translocations (Bell 2010; Bishop et al. 2013; Miller et al. 2014). However, successful translocations and reintroductions require detailed information on the behaviour and ecology of the focal species. Collecting such information on leiopelmatid frogs remains a challenge due to their relatively small size, cryptic patterning, fossorial nature, and lack of a conspicuous call.

Leiopelma hamiltoni (Fig. 1a) is the largest of New Zealand's native frogs with a snout-vent length (SVL) of 34–51 mm (Bell et al. 2004; van Winkel et al. 2018; Bell & Pledger 2023). The colouration of *L. hamiltoni* ranges from dark to light browns with few markings, making individual visual identification difficult (Bell 1978). *Leiopelma hamiltoni* has been extirpated from the North Island and South Island of New Zealand and two naturally occurring remnant populations persist on small, predator free islands in the Marlborough Sounds (northern South Island). *Leiopelma hamiltoni* are nocturnal and rely on fossorial refugia during the day. The most common refuge sites used by *L. hamiltoni* are large natural rock piles in closed canopy broadleaf forests (Bell 1994). Because of their largely fossorial lifestyle, daytime activity cannot be detected by visual searches or other non-telemetry-based techniques. As a result, significant gaps in our understanding of *L. hamiltoni*'s ecology exist, including details regarding breeding and fossorial movements (Bell 1978; Germano & Bishop 2007). *Leiopelma hamiltoni* are also known to occasionally use arboreal habitat when nocturnally active (Bell 1978; Waldman & Bishop 2004; Germano & Bishop 2007; Altobelli et al. 2021). Thus, an ideal tracking technique would deliver accurate detections of individuals both above and below ground.

Leiopelma archeyi (Fig. 1b) is the smallest (SVL = 25–31 mm) of New Zealand's native frogs (van Winkel et al. 2018). There remain only two populations of *L. archeyi* in New Zealand; one population in the Coromandel Forest Park on the Coromandel Peninsula, northeastern North Island, and another in the King Country, western North Island. Unlike the uniform brown body coloration of *L. hamiltoni*, the body coloration of *L. archeyi* varies widely with shades of green, brown, and oranges mottled with distinct dark brown blotch-like patterning (Bell 1978; Thurley & Bell 1994). *Leiopelma archeyi* are considered crepuscular but are often observed active during daylight hours (Bell 1978; Cree 1989) and are frequently found off the ground on vegetation (Cree 1989). When not active, *L. archeyi* use fallen logs, vegetation, and leaf litter as their primary forms of refugia, unlike the rock piles favoured by *L. hamiltoni* (Cree 1989; Bell 1994).

Previously, annual visual search surveys have been the primary method for collecting information on both terrestrial leiopelmatid species. However, visual search techniques only provide very coarse point information on the habitat use of individuals. However, Germano (2006) attempted to use harmonic detection finding to study the homing abilities of *L. hamiltoni* but, the techniques used were found to be unsuitable for long-term use with the technology available. Recently, fluorescent powders have been used to track individual *L. hamiltoni* overnight, providing information on fine-scale overnight habitat use (Ramírez et al. 2017). However fluorescent powders dissipate within hours, not allowing for the continued tracking of individuals across consecutive days. Radio telemetry allows for individuals to be relocated regardless of their activities over consecutive days. Despite the superficial similarities in *L. archeyi* and *L. hamiltoni* body shape, much of the known ecology of these two frogs varies. Thus, the challenges and methodology of telemetry attachment and its suitability for monitoring either species could also vary. In this study we assessed the suitability of a harness radio transmitter attachment technique for use on *L. hamiltoni* and *L. archeyi*. We determined if the harnesses were suitable for use on wild *Leiopelma* by conducting a trial with captive *L. hamiltoni*. We then confirmed the suitability of the harnesses by testing the technique on wild populations of *L. hamiltoni* and *L. archeyi*.

Figure 1. An adult Hamilton's frog (*Leiopelma hamiltoni*) (left) with a telemetry harness attached next to an adult Archey's frog (*L. archeyi*), (right) with telemetry harness attached.

Methods

Harness design

We constructed the harnesses to carry a 0.31 g radio transmitter (Holohil BD-2X, Holohil Systems Ltd., Carp, Ontario, Canada) with a length of tube for attachment around the waist of frogs as described in Bartelt & Peterson (2000) (Fig. 2a). Because the two species of New Zealand terrestrial frogs frequently move in and out of logs, leaf litter, and rock piles, the harnesses had to remain securely attached to the frog without prohibiting their natural fossorial behaviours and movements. Thus, we adapted a design used by Pašukonis et al. (2014a, b) on other small, terrestrial frog species. We used a length of cotton thread threaded through 1 mm external diameter (0.5 mm internal diameter) medical grade silicone tubing which was then threaded through the transmitter tube (Fig. 2b). We selected cotton thread for its propensity to break when placed under strain in the event a frog became entangled in vegetation or could not squeeze through a burrow opening with the transmitter attached. Additionally, if we could not recover a frog to remove the harness, a natural fibre like cotton thread would be a weak point in the harness that would snap as the thread degraded over time. The use of silicone tubing over the cotton thread ensured the harness would glide gently against the delicate skin of the native frogs to prevent binding and rubbing (Rowley & Alford 2007).

Harness attachment

To attach the harness and transmitter to each individual, we cut a length of silicone tubing and slid it underneath the waist of each frog to test fit around the narrowest point of the waist. The circumference of the silicone harness allowed it to slide posteriorly and anteriorly without sliding off the frog. Once the length of the silicone tubing was set, we cut a length of cotton thread and threaded it through the silicone tubing and transmitter tube. We assembled the harness by tying the cotton thread using a square knot and partially tightening the knot (Fig. 2c). We then slid the harness headfirst onto the frog and tightened the square knot, securing the harness to the frog (Fig. 2d). Our method of harness attachment limited frog handling times to roughly 5 minutes which prevented overheating and limited strain and stress.

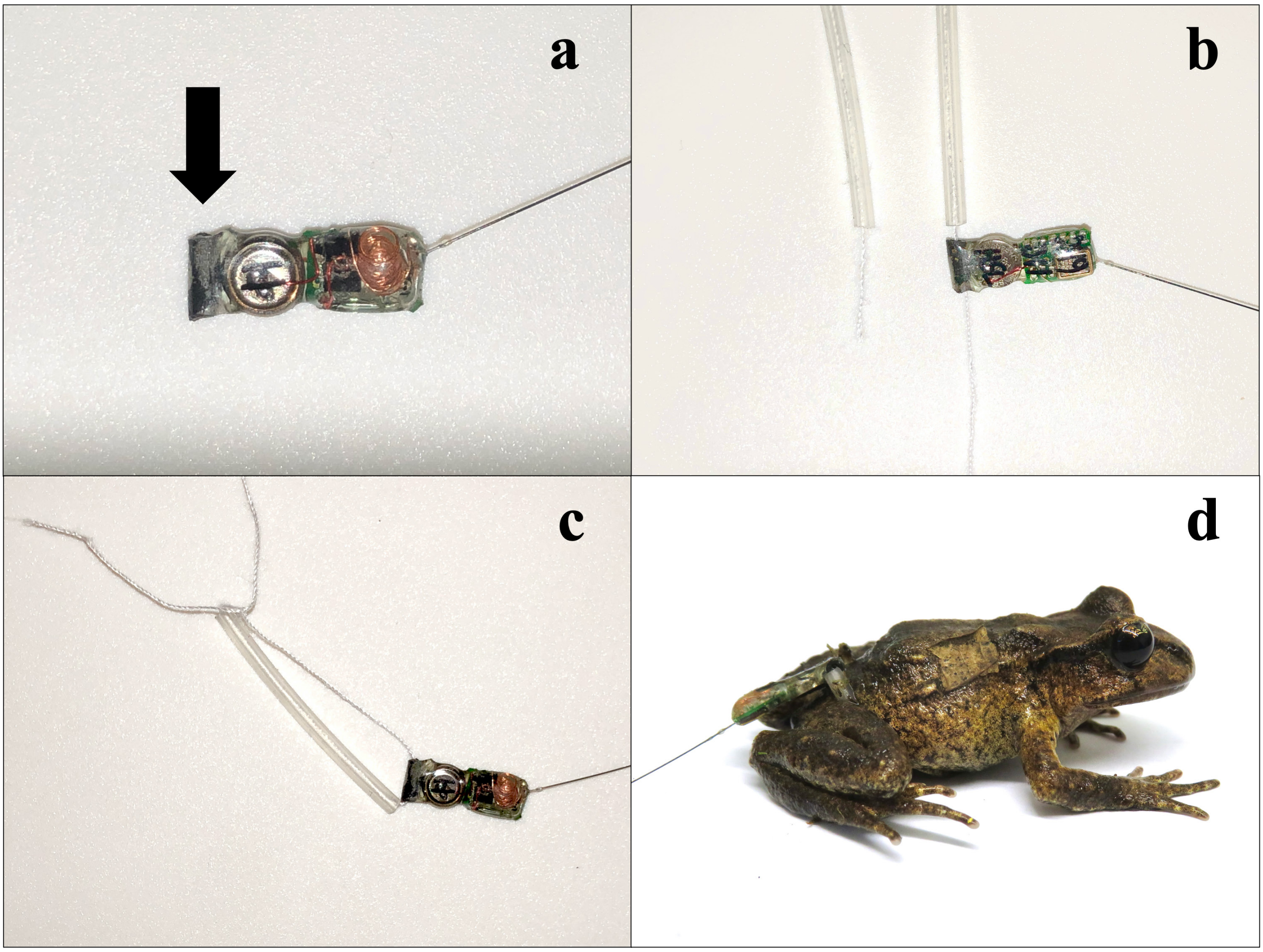

Figure 2. Panels displaying the Holohil BD-2X radio transmitter and the steps used in attaching the harness to leiopelmatid frogs. (a) Arrow pointing to the hard plastic tube epoxied to the BD-2X transmitter used to attach it to a harness. (b) Medical grade 1 mm silicone tubing with cotton thread run through the tube of the radio transmitter and then through the silicone tubing to create the harness. (c) The cotton thread tied using a square knot to form a loop. (d) The square knot fully tightened securing the harness in front of the hind legs of a *Leiopelma hamiltoni*.

Leiopelma hamiltoni laboratory trials

To determine if the harness design was suitable for field use on *L. hamiltoni*, we conducted a laboratory trial from 25 February–20 March 2020 within a temperature-controlled room, located at the Department of Zoology, University of Otago, Dunedin, New Zealand. Four *L. hamiltoni* (individuals: LH1, LH2, LH3, and LH4) were housed in a glass terrarium (length = 90.5 mm, width = 45.5 mm, height = 56.5 mm) with a daily light/dark cycle from 0800 to 1700 hrs. During daylight hours, the room was maintained at 16 °C and at night was maintained at 12 °C. The four individuals in our study shared the terrarium during the entire period of laboratory tests with three other *L. hamiltoni* that were not included in our study and were not equipped with harnesses. The terrarium was designed to simulate the natural habitat of *L. hamiltoni* and contained refuge sites constructed of rock piles and plant material. Indigenous plant species including *Blechnum* fern and *Arthropodium cirratum* were planted in the terrarium substrate and distilled water was delivered through fine mist sprinklers twice daily to maintain humid conditions.

Before attaching a transmitter, we weighed each *L. hamiltoni*. Combined, the harness and the 0.31 g BD-2X transmitter did not weigh more than 10% (Richards et al. 1994) of each individual's body weight (Table 1). Once the harness was attached, we released the frogs back into the tank and observed them daily. As field observations would be for the duration of the battery life of the transmitters, our harnesses needed to remain in place for at least 14 days in the laboratory without causing any injury or abnormal behaviours. If any skin abrasions or injuries were found, we would remove the harness and place the frog into an individual enclosure for observation and recovery before releasing it back into the communal tank. At the end of the study all individuals were weighed again to see if the harnesses had affected the body condition of any individuals. We compared *L. hamiltoni* weights from pre- and post-study using paired *t*-tests and conducted all analyses in R version 4.0.2 (R Core Team 2021).

Leiopelma hamiltoni field trials

From 10 October to 18 October 2020 we conducted visual surveys between 2100–2300 hrs to locate adult *L. hamiltoni* on the small, predator free island of Te Pākeka/Maud Island Scientific Reserve (41°01′ S, 173°53′ E), Marlborough Sounds, northern South Island, New Zealand (hereafter referred to as Te Pākeka). The population of *L. hamiltoni* on Te Pākeka is one of the only remaining naturally occurring populations of *L. hamiltoni* in existence, and thus offers a unique opportunity to study this species' natural behaviour. We conducted surveys within a 16 ha plot of remnant forest. Within the remnant forest, the canopy is comprised of kohekohe (*Didymocheton spectabile*), mahoe (*Melicytus ramiflorus*), pigeonwood/kaiwhiri (*Hedycarya arborea*), and pukatea (*Laurelia novae-zealandiae*). The understory around the rocky banks where *L. hamiltoni* are typically found is dominated by kawakawa (*Macropiper excelsum*) and nikau (*Rhopalostylis sapida*). When *L. hamiltoni* were encountered they were captured and morphometric data was collected. The SVL (mm) and weight (g) of each frog was recorded before they were fitted with a harness and radio transmitter. The harness and transmitter did not weigh more than 10% of an individual's body weight (Richards et al. 1994). After the harnesses were fitted, each frog was released at their original capture location. Each frog was located one to two times per 24 hrs for up to 8 days, after which all frogs that could be located were recaptured. Recaptured frogs had their harnesses removed, were examined for any skin irritation or abrasion around the areas the harness was in contact with, and then weighed before final release. We compared the weight of *L. hamiltoni* when they were first captured and after final capture using a paired *t*-test.

Leiopelma archeyi field trials

To test if our harness design could be used to study *L. archeyi*, we used the same methodology used on *L. hamiltoni* to capture and attach harnesses to *L. archeyi*. From 24 November to 5 December 2020 visual surveys were conducted within the Wharekirauponga (WKP) catchment (38°17′51.8" S, 175°49′18.2" E) of the Coromandel Forest Park, Waikato, northeastern North Island, New Zealand. WKP has historically been a key source of natural resources with a history of kauri (*Agathis australis)* and exotic pine tree (*Pinus radiata*) logging prior to the 1980s. After logging ceased, gold prospecting began within the catchment and continues today (Hotham 2019). As a result, the WKP area is largely regenerated forest comprised of species such as ponga (*Cyathea dealbata*) and rewarewa (*Knightia excelsa*), and *Kunzea robusta*. Despite continuous disturbances and the presence of introduced predators such as Australian brush-tailed possums (*Trichosurus vulpecula*) and ship rats (*Rattus rattus*), the WKP catchment supports the southernmost population of *L. archeyi* on the Coromandel Peninsula. With the multitude of threats to the persistence of

Table 1. Harness information for *Leiopelma hamiltoni* (n = 4) included in the laboratory trials including the weight of each individual before a harness was attached, the number of harnesses the individual had worn at the time of the attachment, the percent of the individual's body weight that the harness comprised, and the number of consecutive days the harness was on the individual.

Individual	Weight (g)	Harness No.	% Bodyweight	Days in harness
LH1	9.6	1	4.3	3
	9.3	2	4.4	1
	9.3	3	4.4	14
LH2	11.3	1	3.6	1
	11.1	2	3.7	8
	11.1	3	3.7	7
LH3	9.8	1	4.2	2
	9.5	2	4.3	20
LH4	11.2	1	3.7	4

L. archeyi within the WKP catchment, radio telemetry has the potential to allow researchers to study the unique survival strategies of this population that has allowed them to endure while others have not.

Individual *L. archeyi* were captured by hand, the SVL (mm) and weight (g) of each frog was recorded, a harness and radio transmitter were fitted to each frog, and then all individuals were immediately released at the point of capture. Despite the smaller size of *L. archeyi*, harnesses and transmitter packages did not weigh more than 10% of any individual's body weight (Richards et al. 1994). We attempted to radio track each individual for a maximum of two weeks or until their radio transmitter failed or the harness detached.

Results

Leiopelma hamiltoni laboratory trials

Within the first four days of laboratory trials three of the four *L. hamiltoni* fitted with transmitter harnesses (LH1, LH2, and LH3) were found without harnesses (Table 1). As a result, we fitted LH1, LH2, and LH3 with tighter harnesses. We fitted LH2 with a harness 5 mm shorter than the original, LH3 with a 3 mm shorter harness, and LH1 with a 4 mm shorter harness. Two days later (2 March), LH1's harness was found (the frog was no longer in the harness) snagged on a *Cyathea dealbata* stump. After visual inspection of the harness and frog, it appeared LH1 was able to slip out of the snagged harness without injury. On the same day, we fitted LH1 with a third harness that was a further 3 mm shorter. After a period of trial and error in achieving the correct tightness of the harnesses, all frogs retained their harnesses for the remainder of the study.

Of the four *L. hamiltoni* that we fitted with harnesses during our laboratory trials, individual LH3 carried a harness for the longest total period (22 days) and most consecutive days (20 days; Table 1). We did not record any significant weight loss among the captive *L. hamiltoni* from the start of the trials to the end (paired *t*-test: $t = 2.8$, df = 3, $p = 0.07$). However, after 14 days of carrying a harness, an abrasion was found on the ventral side of individual LH1, suspected to be the result of a loose harness rubbing against its side. We immediately removed the harness and placed LH1 in a sterile enclosure until the abrasion healed. During this period, we fitted a new individual (LH4) with a harness on 16 March which then remained on the frog until the end of the laboratory trials on 20 March. With the exception of LH1, the remaining *L. hamiltoni* successfully carried harnesses without abrasions and were observed regularly using retreat sites, sharing retreat sites with other individuals, and feeding normally.

Leiopelma hamiltoni field trials

From 10 October to 13 October 2020 we attached harnesses to a total of 20 *L. hamiltoni*. Individuals weighed an average of 7.5 g (range = 5.4–9.3 g, SD = 1.0 g) and had an average SVL of 43.5 mm (range = 39.0–48.8 mm, SD = 2.8 mm) (Table 2). Our constructed harnesses weighed an average of 0.4 g (range = 0.4–0.7 g, SD = 0.2 g) and all harnesses were below 10% of the individual's body weight (average = 5.6 g, SD = 3.6 g).

We were able to track six individuals for eight days, however the majority of individuals were only tracked for 1–7 days ($n = 14$) due to issues with transmitter battery failures. An additional four transmitters unexpectedly stopped producing

Table 2. Results of our in-field harness tests on *Leiopelma hamiltoni* on Te Pākeka/Maud Island Scientific Reserve and *L. archeyi* in the Coromandel Forest Park.

Species	Individual	Weight (g)	SVL (mm)	Days Tracked	Release Wgt. (g)	Fate
Leiopelma hamiltoni	LP5	7.6	46.6	8	7.8	Released
	LP8	9.3	45.9	8	9.0	Released
	LP10	9.1	46.4	8	8.9	Released
	LP11	8.0	45.0	7	8.0	Released
	LP12	7.2	43.7	7	7.5	Released
	LP15	7.3	44.4	8	-	Underground
	LP16	8.9	48.8	3	-	Signal failure
	LP18	7.5	43.8	8	-	Underground
	LP19	6.3	43.1	6	6.4	Released
	LP20	6.9	45.4	8	6.8	Released
	LP21	5.4	39.6	6	5.3	Released
	LP22	7.4	40.0	5	7.2	Released
	LP23	6.6	39.9	5	6.3	Released
	LP24	8.8	46.0	5	8.3	Released
	LP25	6.1	40.3	5	6.0	Released
	LP26	8.0	42.8	5	7.5	Released
	LP27	8.0	42.1	5	7.7	Released
	LP28	7.4	39.0	3	-	Signal failure
	LP29	7.6	43.5	1	-	Signal failure
Leiopelma archeyi	LA11	3.7	33.5	7	-	Dropped transmitter
	LA16	4.5	35.9	1	-	Dropped transmitter
	LA18	3.2	31.5	0	-	Dropped transmitter
	LA20	3.3	29.5	3	-	Signal failure

signals while attached to individuals (Table 2). We were able to recover one of the failed transmitters after spotting the individual LP20 above ground 2 days later. Fourteen of the 20 *L. hamiltoni* tracked were recaptured and had their transmitters removed at the end of our study including the one individual recovered with a failed transmitter. We were unable to remove harnesses from the remaining three individuals with failed transmitters along with two individuals that did not resurface from retreat sites before the end of the study period and could not be reached underground.

All 14 *L. hamiltoni* recaptured at the end of the study period were free of skin abrasion or irritation. The weight of radio tracked individuals on average was significantly lower at the end of the tracking session (average = 7.3 g, SD = 1.1) (paired *t*-test: $t = 2.2$, $df = 13$, $p = 0.02$) compared to when transmitters were first attached (average = 7.5 g, SD = 1.2).

Leiopelma archeyi field trials

Out of the 20 individuals captured during our surveys, only four weighed over the 3 g minimum mass required to carry a transmitter and were therefore fitted with a transmitter. Radio tracked *L. archeyi* weighed on average 3.7 g (range = 3.2–4.5 g, SD = 0.6 g) with an average SVL of 32.6 mm (range = 25.9–35.9 mm, SD = 2.7 mm).

We were able to track one individual (LA11) for seven days (30 November–6 December) before locating the transmitter and harness in leaf litter near the individual's most recent retreat site (Table 2). We found detached harnesses from two other individuals within 24 hours of initial release (LA16 and LA18; Table 2). At the end of the study period we were unable to locate any of the *L. archeyi* to inspect them for skin abrasions or to measure potential changes in weight. This includes individual LA20, which we were unable to recapture to remove the harness and transmitter due to its transmitter unexpectedly failing. However, during the time the *L. archeyi* were carrying harnesses, we were able to accurately locate them within dense vegetation, up to 1 m beneath leaf litter, and underground.

Discussion

Leiopelma hamiltoni laboratory trials

The results of our laboratory trials of the waist-harness telemetry attachment showed that despite the anatomical and ecological difficulties associated with attaching telemetry packages to amphibians, they are satisfactory for use on *L. hamiltoni* frogs. After an initial acclimation period of 24 hours, harnessed individuals were regularly observed moving in and out of refugia within the tanks uninhibited by the harnesses and transmitter packages. In addition, the harnessed individuals continued to share retreat sites with other frogs and to feed and maintain weight similarly to individuals not included in this study in the communal tank. While the waist-harness design did not appear to have an impact on the *L. hamiltoni*'s behaviour, it did expose issues that needed to be resolved before the harnesses could be used in the field.

While none of the captive *L. hamiltoni* with waist-harnesses displayed skin abrasions during the first 13 days of observation, individual LH1 was removed from the study at day 14 after developing an abrasion on its ventral side believed to be caused by abnormal rubbing of the end of the silicone tubing against the individual's side. Although the limited battery-life of the transmitters we selected for the field trials meant no individual would carry a harness for more than 14 days, all subsequent harnesses were adjusted so the silicone tube pressed tightly against the side of the transmitter package to limit potentially abrasive surfaces on the harnesses. As a result, no additional individuals in the remaining laboratory trials or in any of the field trials displayed abrasions caused by the harness. Further, as individual LH3 was able to continuously carry a harness for 22 days without showing signs of injury or irritation, our laboratory trials also showed the potential of the waist-harness in combination with a telemetry package to continually monitor individual *L. hamiltoni* for periods longer than had been possible before (Germano 2006; Ramírez et al. 2017).

Similar waist-harness designs have been used for long-term observations of other species of frogs by recapturing and replacing failing transmitters with fresh units, extending observation periods up to hundreds of days (Miaud & Sanuy 2000; Bartelt et al. 2004; Goates et al. 2007; Yetman & Ferguson 2011; Liang 2013; Sepulveda & Layhee 2015; Stockwell et al. 2016). For example, using a similar harness design as described here, researchers were able to monitor post-breeding behaviour of wood frogs (*Lithobates sylvaticus*) for over 100 days by recapturing and replacing transmitters every four weeks (Freidenfelds et al. 2011). It is possible by using similar recapture and replacement techniques future researchers could monitor Leiopelmatid frogs across multiple seasons or potentially across years. However, the effects of waist-harnesses are known to vary by species (Rowley & Alford 2007) and previous long-term studies have focused on species that are often larger than leiopelmatid frogs. Future studies attempting to extend the observation period on leioplematids beyond two weeks should conduct controlled pilot studies to confirm the harness suitability and examine individuals daily to limit the risk of injury or death.

Leiopelma archeyi and *L. hamiltoni* field trials

Of the 20 *L. hamiltoni* on Te Pākeka originally fitted with waist-harnesses, all but six frogs were recaptured by the end of the trials. While ideally no individual would be left in the field with a transmitter attached, this is a recognised risk of conducting radio telemetry studies as transmitters fail unexpectedly or individuals cannot be relocated in time. As such, the harness design we selected purposefully used cotton thread for its ability to naturally deteriorate over time. Thus, the six individual *L. hamiltoni* left in the field with harnesses attached would have likely carried the failed transmitters for an additional few weeks before the cotton thread deteriorated and the harnesses detached (Waye 2001). The 14 *L. hamiltoni* recaptured at the end of the trials showed no signs of skin irritation or skin damage at the time of harness removal. Although the average weight of the recaptured individuals significantly decreased (−0.2 g), the weight loss could have be related to natural variations in water loss that could have affected any frogs within the population with or without transmitters attached. Individuals were initially captured during rainy evenings when native New Zealand frog activity is thought to be at its peak (Cree 1989). However, frogs were opportunistically recaptured at the end of the trials often in drier conditions. As the mass of frogs is known to fluctuate based on evaporative water loss and rehydration (Thorson 1956; Cree 1985, 1989), the most likely reason for the observed weight loss among the recaptures is due to the drier conditions on Te Pākeka during recapture. As the primary concerns with attaching transmitters to amphibians are the impact the attachment will have on the behaviour, delicate skin, and overall health of the study subjects, the observations collected during our field trials provide support that a waist-harness design is a suitable and effective method to conduct short-term tracking on *L. hamiltoni*.

While all radio tracked *L. hamiltoni* ($n = 20$) retained the waist-harness for our full observation period on Te Pākeka, the harnesses detached from three of the four the *L. archeyi* tracked in the Coromandel Forest Park. These harness retention failures were likely caused by improper harness fit because of the subtle differences in morphology and behaviour between *L. hamiltoni* and *L. archeyi*. Further, while we were able to test the waist-harness design on captive *L. hamiltoni*, we did not have access to captive *L. archeyi* to test the design and fit before our field trials. Despite similarities in movement and body structure of *L. archeyi* and *L. hamiltoni,* the smaller size of *L. archeyi* prevented us from securing the 1 mm silicone tubing tight enough around the waist of the individuals to prevent escape. Future waist-harnesses should be constructed with a more flexible smaller diameter silicone tubing so that the harnesses can be tight enough to prevent the smaller *L. archeyi* from manoeuvring out of the waist-harness. Smaller diameter tubing will also allow researchers to decrease the overall weight of the harness and telemetry package thereby improving its suitability for use with *L. archeyi*.

The poor harness retention on *L. archeyi* was probably also compounded by the more arboreal behaviour and complex environments used by *L. archeyi* relative to *L. hamiltoni*. *Leiopelma archeyi* were commonly found in dense leaf litter or off the ground using grasses and other vegetation as refugia. The frequent use of above-ground vegetation by *L. archeyi* compared to *L. hamiltoni* probably increased the risk that the harnesses would become entangled as *L. archeyi* moved through their environment. For example, individual LA16 was tracked to a dense tussock of the sedge *Carex geminata* where the harness had become entangled, with *Carex geminata* leaves wrapped between the harness and the individual's body most likely due to the loose fit of the harness. While the animal was found alert and healthy, a properly fitted harness would reduce the risk of entanglement which is a common risk associated with externally attached telemetry devices and should be considered a potential risk regardless of harness fit.

Despite the low retention of waist-harnesses by *L. archeyi*, none of the four individuals tracked showed signs of injury or abnormal behaviours while the harnesses were attached. Had we been able to test the fit of the waist-harnesses on a captive population of *L. archeyi* as we were with *L. hamiltoni*, it is likely we would have been able to correct for many of the design issues discussed. As a result, the waist-harness design described here may not currently be as suitable for telemetry studies on *L. archeyi* but could be refined for future use.

As researchers and conservation managers explore methods to collect more detailed information on these two threatened species, our study has shown that radio telemetry provides a useful technique to acquire valuable observations. However, despite the similarities in overall body shape, the narrower waist of *L. archeyi* compared to *L. hamiltoni* resulted in frequent harness loss in *L. archeyi*. This difference in design success between *L. hamiltoni* and *L. archeyi* is an example of how the morphology and behaviour of a species will determine the impact and efficacy of a telemetry package. While we are confident the issues with harness fit on *L. archeyi* can be corrected in future applications, our experience highlights the need for species-specific testing of even established and trusted telemetry techniques when applied to a new species of frog.

Leiopelma archeyi and *Leiopelma hamiltoni* are two of the most evolutionarily distinct and globally endangered amphibian species in the world (Zoological Society of London 2021). Despite past work by researchers (Cree 1989; Bell et al. 2004; Germano 2006; Ramírez 2017), key information on the natural history of both species including daily activity patterns, reproductive behaviours, and intraspecific interactions remain unanswered. The use of the radio telemetry techniques tested and discussed represents a major advance in allowing researchers to expand observations beyond the traditional visual search data that has thus far been the preferred method of data collection for Leiopelmatid frogs. The use of similar waist-harness telemetry packages for extended observation periods will allow a more detailed understanding of *Leiopelma* habitat use, especially at times when they are undetectable (e.g. using refuges). This method will also allow researchers and wildlife managers to monitor the success of future *Leiopelma* translocations within New Zealand and bolster our understanding of these cryptic and basal frogs.

Acknowledgements

We would like to dedicate this study to Debbie Bishop and her continued commitment to amphibian conservation and to the team that made this issue possible. We would like to thank the Iwi and practitioners who contributed to this study, The Ngāi Tahu Research Consultation Committee, Ngāti Kuia, the Department of Conservation including Emmanuel Oyston, Anna Star and whānau, Marc and Jane Lelec, and the Frog Recovery Group. We would also like to thank Aidan Mora-Teddy, Liam Ireland, Jenna Powell, and Sarah Lamar for their contributions in the field. We also thank OceanaGold Waihi and the Society for Research on Amphibians & Reptiles in New Zealand for their financial and logistical support.

Additional Information and Declarations

Conflicts of interest: The authors declare no conflicts of interest.

Funding: Funding for this project was provided by the University of Otago, OceanaGold Waihi, and from the Herpetological Research Award provided by the Society for Research on Amphibians and Reptiles in New Zealand (SRARNZ).

Ethics: All frogs included in laboratory and field trails were done so with authority from the University of Otago Animal Ethics Committee (authorisation number AEC 107/15 and AUP-19-200), with approval from Ngāti Kuia and Ngāi Tahu, and under a Department of Conservation permit (authorisation number 48418-FAU, 53687-FAU, and 82490-FAU).

Data availability: Data regarding frog recaptures and the code used in this article in Program R is openly available from the corresponding author upon request.

Author contributions: JTA and PJB conceptualised this study. JTA established the methods and undertook the investigation. JTA drafted the original manuscript and JTA, KJMD, SSG undertook reviews and editing. All authors administered aspects of the project.

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Accepted: 12 January 2022; received: 21 May 2022
Editorial board member: Javiera Cisternas