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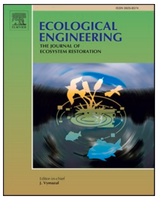

Freshwater turtle climbing abilities: Implications for the design and use of shoreline erosion control structures

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ABSTRACT

Freshwater shoreline modifications can reduce connectivity between aquatic and terrestrial environments, contributing to the decline of freshwater biodiversity. Freshwater turtles may be particularly vulnerable to shoreline modifications because they must access land for essential activities such as nesting, basking, and dispersal. Here, we tested the clinging abilities of three freshwater turtle species (i.e., painted turtles, *Chrysemys picta*; eastern musk turtles, *Sternotherus odoratus;* and northern map turtles, *Graptemys geographica*) to inform design criteria for mitigating the impacts of shoreline modifications on the ability of turtles to perform these behaviours. We tested clinging behavior using a ramp and pulley system with smooth and rough concrete ramps to find the maximum clinging angle for all three species. We found that painted turtles were the weakest at clinging, averaging a maximum clinging angle of 37° on a smooth ramp and 73° on a rough ramp. Eastern musk turtles had an average maximum clinging angle of 45° on a smooth ramp and 87° on a rough ramp. Northern map turtles had an average maximum clinging angle of 41° on a smooth ramp and 87° on a rough ramp. For all three species, surface type had significant effects upon maximum clinging angles, and mass was also statistically significant in affecting the clinging of eastern musk and northern map turtles. As the painted turtles were the weakest clingers and the most ubiquitous species (Van Dijk, 2016), we used this species to validate the clinging trials through volitional climbing tests. Successful climbs peaked at 35° on the smooth ramps and 40° on the rough ramps. To maintain turtle accessibility in areas with these species, future shoreline modifications should be textured and not have slopes that exceed 40°.

1. Introduction

Currently, more than half of the global population lives within three kilometers of freshwater (Kummu et al., 2011), and, unsurprisingly, human activities often negatively impact freshwater ecosystems (Reid et al., 2019). Civilization depends on freshwater ecosystems for transportation, irrigation, and drinking (Fang and Jawitz, 2019). However, human activities can be in conflict with the integrity of freshwater ecosystems, including riparian areas, which are increasingly used for residential and recreational purposes (Gittman et al., 2021; Schmieder, 2004; Vadeboncoeur et al., 2011). These activities often result in shoreline alterations, and freshwater life may be directly impacted as shoreline property owners alter riparian zones to mitigate erosion and flooding or for aesthetic purposes. These alterations range from armored shoreline retaining walls to replacing natural environments with lawns and imported sand and rocks (Brauns et al., 2007; Schmidt, 2008). Furthermore, shoreline modification may also involve the loss of natural structures, such as fallen trees and aquatic vegetation which ultimately degrade the ecological integrity of riparian ecosystems (Brauns et al., 2011; Dustin and Vondracek, 2017; Ness, 2006; Wehrly et al., 2012).

Shoreline modifications can negatively impact many aquatic and semi-aquatic species. For instance, littoral modifications reduce the diversity of macroinvertebrates and macrophytes (Miler and Brauns, 2020; Porst et al., 2019) and can contribute to the decline of bird populations (Kaufmann et al., 2014). Moreover, shoreline degradation promotes eutrophication from urban and agricultural run-off (Bertness et al., 2002), further exacerbating freshwater biodiversity loss (Meerhoff and de los Ángeles González-Sagrario, 2022). Restoring shorelines to their original states, such as through the removal of retaining walls, lowering slope angles, and replanting vegetation, can decrease phosphorous and nitrogen loads and increase carbon uptake (Symmank et al., 2020) and potentially restore the abundance and diversity of wildlife.

Freshwater turtles may be particularly vulnerable to shoreline alterations, because many species exhibit site fidelity (Bernstein et al.,

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2007; Lefevre and Brooks, 1995), and because altered shorelines may impede or prevent dispersal as well as movements to basking sites and nesting areas (Winters et al., 2015). Freshwater turtles bask for thermoregulation (Bulté and Blouin-Demers, 2010a), epidermal health (Boyer, 1965), and hormonal regulation (Ganzhorn and Licht, 1983). Moreover, female turtles require shoreline access to reach nesting sites (Gibbons, 1968). Habitat loss through shoreline modification may interfere with these aforementioned activities, potentially influencing individual health and reproduction as well as population-level processes. Information about the capabilities of turtles to maneuver over artificial terrain could thus inform the selection of shoreline modifications that do not impede access to riparian habitats. This is vital when considering that over half of chelonian species are at risk of extinction, with habitat loss being a leading threat to their population decline (Stanford et al., 2020).

The slope and texture of artificial shorelines can presumably influence the movement of turtles and the connectivity between freshwater and terrestrial habitats. For instance, if a retaining wall is too steep or too smooth, turtles may be unable to climb it to access essential habitats. Little is known, however, about the climbing capabilities of turtles, and the few studies available focused on terrestrial species (Claussen et al., 2002; Claussen et al., 2004; Muegel and Claussen, 1994; Willbern, 1982; Xiao et al., 2021) or were conducted to develop barriers for roads intended to exclude or guide freshwater turtles (Aresco, 2005; Heaven et al., 2019; Ives-Dewey and Lewandowski, 2012). To our knowledge there is no information specific to the climbing capabilities of freshwater turtles to inform shoreline alteration regulations and practices that maintain connectivity between fresh waters and riparian areas.

Here we examined the effects of slope angle and substrate texture on the climbing abilities of common freshwater turtle species in Eastern North America. We focused on concrete, using both smooth and rough surfaces. Concrete continues to be widely used in freshwater environments, such as for erosion control and for harbor infrastructure (Cooke et al., 2020), and is thus a logical material to use for such experiments. And while concrete is not the optimal material for shoreline modification, there are cases of concrete erosion control structures that are an overall benefit to the environment (Cooke et al., 2020). Furthermore, our goal was to inform the design of erosion control structures that minimally disrupt essential turtle behavior such as basking, nesting, and dispersal. Also, through understanding substrate texturing effects and optimal slope angles for turtle access, we hoped to contribute to the renaturalization of degraded riparian environments. We focused on three species representing a range of sizes with differing niches: the painted turtle (*Chrysemys picta*), the eastern musk turtle (*Sternotherus odoratus*), and the northern map turtle (*Graptemys geographica*). The painted turtle is a small pond turtle that can be found in a diversity of environments, from lake borders to marshes to slowly flowing streams (Bury and Germano, 2003; Cagle, 1954). The eastern musk turtle is a small bottom crawler that is predominantly found in slowly flowing, shallow water bodies with extensive vegetation (Belleau, 2008). The northern map turtle is a medium size river turtle that frequents larger water bodies, such as lakes and rivers (Gordon and MacCulloch, 1980). Also, all three species are currently listed as Special Concern under the Canadian federal *Species at Risk Act* (Government of Canada, 2023). First, we conducted forced clinging trials with all three freshwater turtle species to create a baseline for understanding general turtle capabilities before more extensive climbing trials were conducted. Then, we used painted turtles, a species known for its basking habits and commonness in nature, for the volitional climbing tests.

2. Methods

2.1. Study site and turtle collection

Painted, eastern musk, and northern map turtles were captured using fyke nets and snorkeling with dip nets in Lake Opinicon, Eastern Ontario, Canada (44°34′ N, 76°19′ W) throughout May and June 2022. All captured turtles were brought to the Queen's University Biological Station on the shore of Lake Opinicon where they were identified and/or marked and individually weighed. To ensure that turtles were not reused, we noted individual identifications (carapace notches or Passive Integrated Transponder tags) and captured turtles from different location on the lake. All procedures were approved by the Carleton University Animal Care Committee and were conducted under the terms of a Scientific Collection Permit from the Ontario Ministry of Natural Resources and Forestry and a Species at Risk Permit from the Ontario Ministry of Environment, Conservation and Parks.

2.2. Clinging abilities

To test the maximum slope that turtles can cling to, two concrete ramps (0.457 by 1.219 m) were used, one with a smooth surface, and the other with 6.4 mm width grooves every 12.7 mm (Fig. 1).

Concrete (self-leveling LevelQuik RS) was used, as it is easy to manipulate and is a common material used in shoreline modifications. The corners of one side of the ramp were connected to a pulley system that enabled the slope to be raised from 0° to 90°. A pocket on the side of the ramp held an iPhone that was used to measure ramp angle via the Angle Pro application. For these indoor tests with ambient temperatures that ranged between 15.5 and 22 °C, turtles were individually placed in the centre of the ramp. We ensured that the turtle was gripping the ramp by observing that their feet were on the concrete surface before initiating the test. To test clinging ability, the ramp was slowly raised, and the angle at which the turtle slid (i.e., failure to continue clinging) was noted. A researcher held their hands below each turtle to protect them from falling to the floor. To account for potential order effects, the turtles were randomly assigned to start with either the smooth or the rough surface. Each turtle was tested three times with both treatments, and we ensured at least a 10-min rest period in between trials. The maximum clinging angle was taken for each treatment (smooth surface and rough surface).

2.3. Climbing success

Volitional climbing abilities were tested outdoors with painted turtles. In conjunction with a water circulation system, two 1000 L tanks were used with a water depth of 0.483 m, one for the smooth ramp tests (Fig. 2) and one for the rough ramps tests. As for the prior test, smooth and rough concrete ramps (0.356 by 1.219 m) were created, using the same grooved parameters. The ramps were able to be manually adjusted for specific angles, which were found using the iPhone Angle Pro application. Individual turtles were randomly assigned to start at either smooth ramp or rough ramp and they were tested at angles from 25° to 45° for the smooth ramps and from 30° to 70° for the rough ramps. Preliminary trials were conducted on separate painted turtles to have a general idea of the range of slope angles that painted turtles would climb. Trials ran for 5 h, and cameras were programmed to capture photos every minute. A successful trial was noted if a turtle climbed the

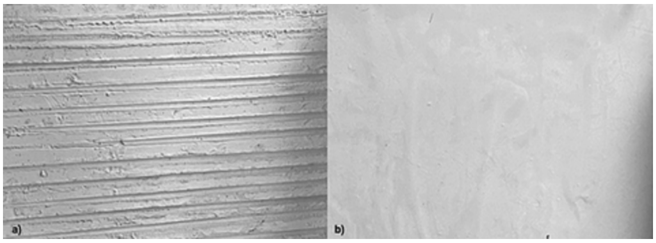

Fig. 1. a) The texture of the concrete ramps used in the clinging tests: a) rough with 6.4 mm grooves every 12.7 mm and b) smooth using self-leveling concrete (LevelQuik RS).

Fig. 2. A photo of a painted turtle taken in between smooth ramp trials in the outdoor climbing tests.

ramp so that all four feet were out of the water. Water temperature measurements were taken once per trial and ranged between 13 °C and 18 °C. We maintained the water temperature in the tank relatively low compared to the ambient temperature to entice turtles to bask because turtles tend to bask less when water temperature is high compared to air temperature (Bulté and Blouin-Demers, 2010b). The selected temperatures are similar to spring temperatures at our latitude (Bulté and Blouin-Demers, 2010b; Edwards and Blouin-Demers, 2007) which is the time at which turtles bask most heavily (Bulté and Blouin-Demers, 2010b). While the water temperature may have decreased the locomotor performance of turtles (Ben-Ezra et al., 2008), it makes our test more conservative since our goal is to identify angles at which turtles show high climbing success. Also, as the trials were conducted outdoors, water temperature fluctuation could only be partially controlled, with the sun and ambient temperatures necessarily affecting water temperature. Finally, as the tanks were located outside, barrier tape and no-entry signs were erected to ensure that the turtles were not disturbed during testing.

2.4. Data analysis

We used R version 4.0.5 for all data processing and analysis. The initial data importation and assessment was done with tidyverse version 1.3.2 (Wickham et al., 2019). To evaluate the treatment effect, we fitted a Gaussian mixed effects regression model where the response variable was maximum clinging angle, using the package lme4 version 1.1–28 (Bates et al., 2015). The fixed effect predictor variables in this model were surface type, sex and body mass, and the model also included a random effect of turtle identity to account for repeated measures of the same individuals ($n = 3$ measures of 38 painted turtles, 44 eastern musk turtles, and 39 northern map turtles), and regression models were developed for each species separately. We used the package lmerTest version 3.1–3 (Kuznetsova et al., 2017) to obtain *p*-values for the fixed effect predictors using Satterthwaite's method. We also used the package visreg version 2.7.0 (Breheny and Burchett, 2017) to visualize the effect of each predictor, and we verified that the assumptions of normally distributed residuals were met.

3. Results

3.1. Clinging abilities

Thirty-seven painted (20 males, 17 females), 44 eastern musk (24 males, 20 females), and 43 northern map (18 males, 21 females, 4 unkown) turtles were captured and marked for the clinging trials. For painted turtles on the smooth surface, the average maximum clinging angle was 35.0° for females and 38.2° for males (Fig. 3). On the rough surface, the average maximum clinging angle was 78.0° for females and 69.2° for males. The additive mixed effects model also indicated that surface type, and not sex or mass, had a significant effect upon maximum clinging angles (Table 1). For eastern musk turtles on the smooth surface, the average maximum clinging angle was 42.0° for females and 48.1° for males (Fig. 4). On the rough surface, the average maximum clinging angles was 86.2° for females and 87.2° for males. The additive mixed effects model indicated significant effects of the surface type and mass upon maximum clinging angle, while sex did not have significant effects (Table 1). For northern map turtles on the smooth surface, the average maximum clinging angle was 40.7° for females and 40.8° for males (Fig. 5).

On the rough surface, the average maximum clinging angle was 87.3° for both females and males. The additive mixed effects model indicated significance for surface type and mass effects on maximum clinging angle, while sex did not have significant effects on maximum clinging angle (Table 1). Four turtles were too young to be properly sexed (carapace length < 88 mm), and these turtles had an average maximum clinging angle of 45.8° on the smooth surface and 84.0° on the rough surface.

3.2. Climbing success

For volitional climbing behavior in painted turtles, we tested 14 males and 11 females. On the smooth ramps, successful climbing peaked with 18 of the 25 turtles (72%) for both 30° and 35° slope angles and drastically decreased to 8 of the 25 turtles (32%) at 40° and 0 turtles at 45° (Fig. 6). For the rough surface, successful climbing peaked at 21 of the 24 turtles (88%) for both 35° and 40° slope angles and slowly dropped in success to 6 of the 24 turtles (25%) at 70° (Fig. 6).

4. Discussion

The objectives of this study were to further understand how turtles may respond to shoreline alterations and restoration. Through our clinging tests, we found that all three species of turtles (i.e., painted, eastern musk, and northern map) were substantially better at clinging to a rough concrete surface than to a smooth surface, showing the importance of considering texture when designing artificial shorelines. Shoreline structures should be textured enough to allow turtles to climb on them and access terrestrial habitats. Moreover, our results demonstrated that not all turtle species have equal clinging abilities. Painted turtles had a lower threshold for clinging to steep angles than eastern musk and northern map turtles. When building shoreline structures, it would be beneficial to account for the weakest climber to ensure that all species have adequate access. Given that painted turtles appear to be the weakest climbers, we recommend using the results from the painted turtle tests to guide the design of artificial shorelines in environments where this species is present.

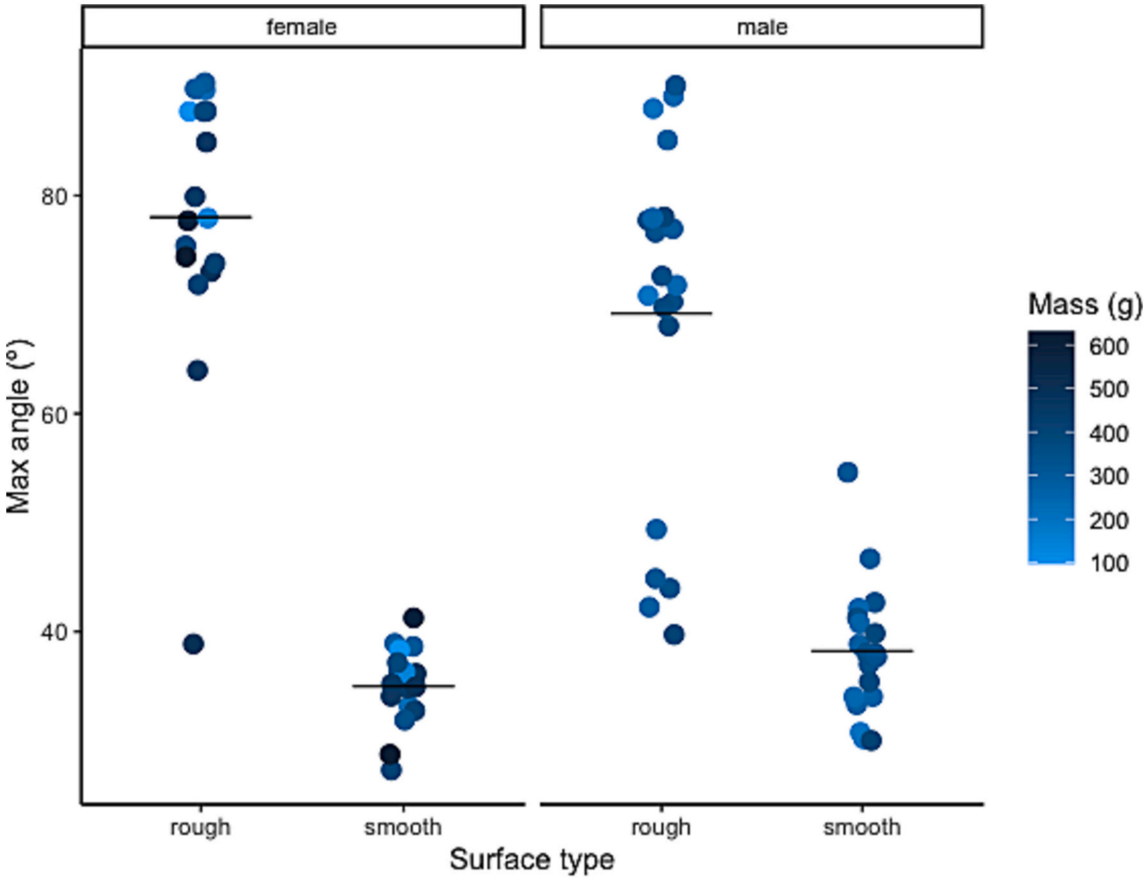

Fig. 3. The maximum clinging angle for painted turtles with regard to smooth and rough surface types and sex with a body mass gradient indicated by darker blue for heavier turtles. Horizontal lines indicate the group means. The means and standard errors for females were 78.0 +/− 3.1° on the rough ramp and 35.0 +/− 0.86° on the smooth ramp, and for males, they were 69.2 +/− 3.6° on the rough ramp and 38.2 +/− 1.3° on the smooth ramp. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Additive mixed effects model p-values for treatment effects upon the response variable of maximum clinging angle for painted (n = 3 test of 37 individual turtles), eastern musk (n = 3 tests of 44 individual turtles), and northern map (n = 3 tests of 39 individual turtles) turtles with the predictive variables of surface type, sex, and mass. Statistically significant p-values are in bold font.

	Painted		Eastern musk		Northern map	
Predictor variables	p-value	SE	p-value	SE	p-value	SE
Surface type	**<0.001**	2.592	**<0.001**	1.545	**<0.001**	0.909
Sex	0.099	2.760	0.132	1.608	0.348	1.363
Mass	0.054	0.013	**0.010**	0.014	**0.034**	0.001

We validated the clinging test's results using the volitional climbing tests with painted turtles. The maximum angles of the volitional tests were much lower than those of the clinging tests, indicating that turtles may not have the physical attributes needed to pull themselves up at their higher maximum clinging angles. Additionally, it is important to understand that freshwater turtles are morphologically diverse (Claude et al., 2003), which may impact their abilities to pull themselves up steep slopes. Indeed, turtle sizes vary, both within and between species, and morphology and size are likely to affect climbing ability. Therefore, to build appropriate shoreline structures, it is vital to know both what species are locally present, and what their morphological attributes are.

Previous studies have assessed the climbing abilities of species that are considered terrestrial. For example, eastern box turtle (*Terrapene carolina carolina*) can climb slopes up to 60° (Muegel and Claussen, 1994) while the keeled box turtle (*Cuora mouhotii*) and the flowerback box turtle (*Cuora galbinifrons*) can climb slopes up to 90° (Xiao et al., 2021). Claussen et al. (2002) tested the locomotion of the ornate box turtle (*Terrapene ornata ornata*) on slopes between −40°, and + 40° and found that turtles could easily move up the +40° slope but were only 25% successful at moving down the −40° slope. Willbern (1982) anecdotally reported ornate box and three-toed box (*Terrapene carolina triunguis*) turtles climbing the corners of a vertical, wire mesh fence. To our knowledge, the only other insights on the climbing ability of freshwater turtles comes from Moore and Seigel (2006) who observed that the yellow-blotched map turtles (*Graptemys flavimaculata*) in the Pascagoula River, Mississippi, USA struggled to climb clay slopes with angles >45°. It is obvious that climbing abilities widely varies among turtle species, which further emphasizes the importance of adapting shoreline slope regulations to be specific to local turtle species climbing capabilities.

Sex did not affect clinging abilities as it was not a statistically significant factor, but the volitional tests showed greater disparity between the sexes for climbing abilities. Sexual dimorphism may explain this difference, where males were more successful at climbing, except for on the rough ramps with slopes >55°. For example, mature females are larger, heavier, and have greater carapace volume than males (Jolicoeur and Mosimann, 1960; Rowe, 1997). A larger size and mass could have both positive and negative effects on climbing. For instance, a heavier turtle may struggle harder against gravity, hindering climbing. Conversely, a larger and heavier individual may have the greater strength necessary to pull itself up a steep terrain. The effects of mass on climbing could be applied to differences observed between species, as well. Sexually mature painted turtle males also have longer and straighter foreclaws in comparison to females (Ernst, 1971; Gibbons,

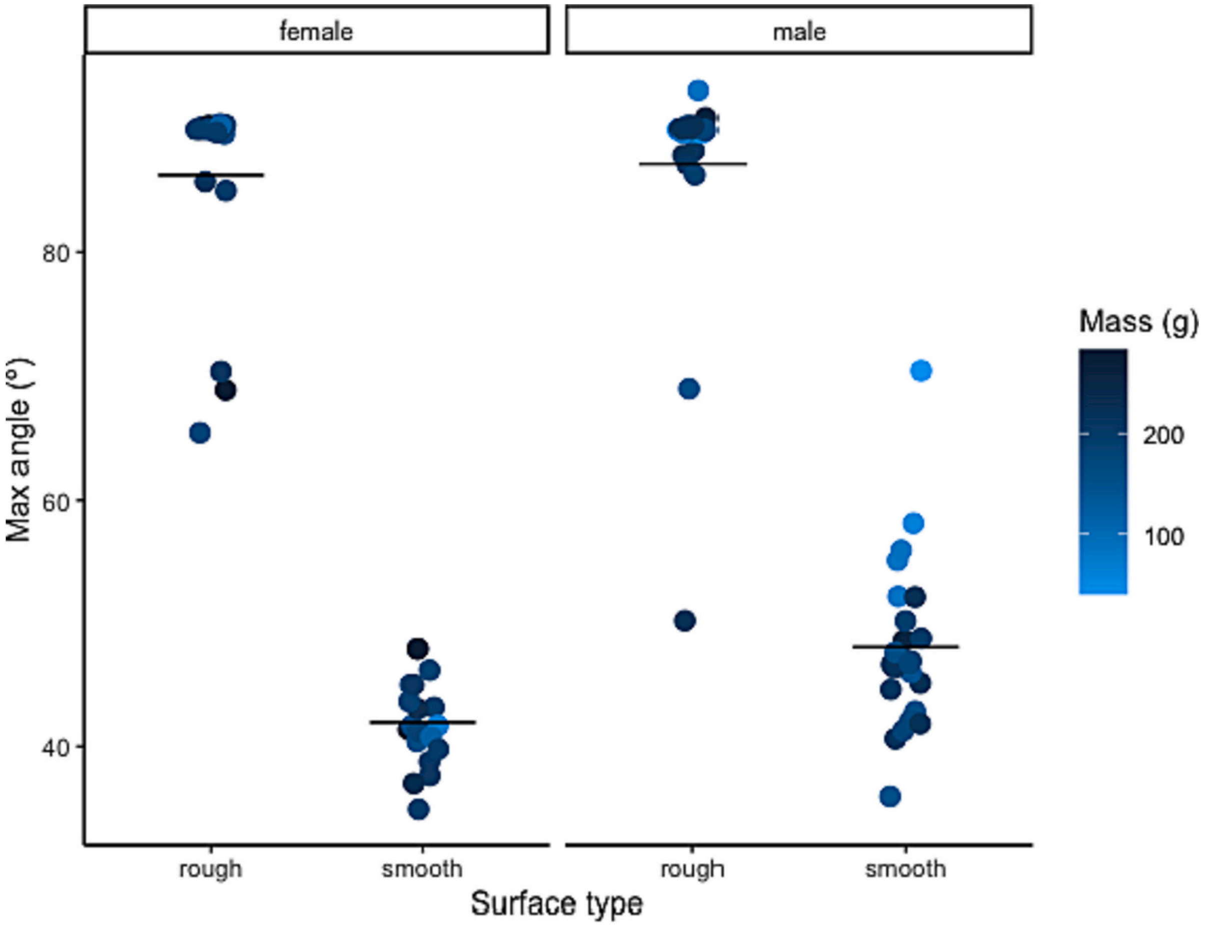

Fig. 4. The maximum clinging angle for eastern musk turtles with regard to smooth and rough surface types and sex with a mass gradient indicated by darker blue for larger masses and the means indicated by a line. The means and standard errors for females were 86.3 +/− 1.8° on the rough ramp and 42.0 +/− 0.77° on the smooth ramp, and for males, they were 87.2 +/− 1.9° on the rough ramp and 48.1 +/− 1.4° on the smooth ramp. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1968), which they use in courtship (Berry and Shine, 1980). While foreclaws may not be needed for climbing at low angles, they may become more of a factor for gripping at steeper angles. Therefore, straight foreclaw shape may hinder the climbing ability of males at the steepest rough surface angles, offsetting the benefits males may experience from being smaller and less constrained by their weight. However, the exact effects of elongated foreclaws upon moving capabilities have not been studied. Also, red-eared slider turtles (*Trachemys scripta elegans*), morphologically similar to painted turtles, have sexually dimorphic hind claws, longer in females for nest digging (Warner et al., 2006), which may enhance their climbing abilities through added grip strength.

It is possible that learning plays a role in climbing ability as suggested by our results from the volitional climbing experiment. The first trial for each individual started at the lowest angle, with each proceeding trial being at a slightly steeper angle. The first trials for both ramp types had lower percentages of successful climbing turtles than the following second lowest angle. For example, the smooth ramp at 25° only had a 56% climbing success rate, while the 35° angle had 72% success. Similarly, the rough ramp climbing success was 79% at 30° and 88% at 35°. Painted turtles may have the ability to learn in their natural environment, as turtles living around human-made structures would have a greater opportunity to learn. A learning capability may also counter another sex-based difference observed during testing: the timidity of female painted turtles. This behavior was witnessed during both the clinging tests, where females were more prone to retract into their shells when they perceived the presence of humans, as well as between the climbing tests and during ramp adjustments, whereas males were less likely to hide beneath structures. If a sexual difference in timidity explains the climbing differences between males and females, given enough time to learn or acclimate, females may reach the same climbing ability as males.

We have demonstrated that to be accessible to turtles, shoreline modifications would benefit from texturing, as a rough substrate enables increased movement at higher angles. Previous studies corroborate that substrate type affects turtle movement. For example, ornate box turtles displayed slower movement on sand than on Styrofoam, which was tied to their abilities to grip and to apply downward force (Claussen et al., 2002; Claussen et al., 2004). However, textured shorelines become largely inaccessible to painted turtles if they exceed 40° angles. Therefore, future shoreline restorations and modifications should not exceed this slope to ensure that turtles can access terrestrial habitats and basking sites. We used concrete for this experiment given that it is still a commonly used material in shoreline alterations and erosion controls (Cooke et al., 2020). However, alternatives such as rip-rap (a rock armored erosion control) or other nature-like solutions require further study and may overall be more beneficial for biodiversity than concrete. Also, it should be acknowledged that this study was not able to include all local species, and future studies should explore the climbing abilities of turtles that are native to their area. Failing to account for species-specific abilities could have negative consequences upon populations unable to access essential habitats needed to complete their necessary turtle life-history activities. Looking to the future, shoreline modifications will continue to be an aspect of shoreline management, and

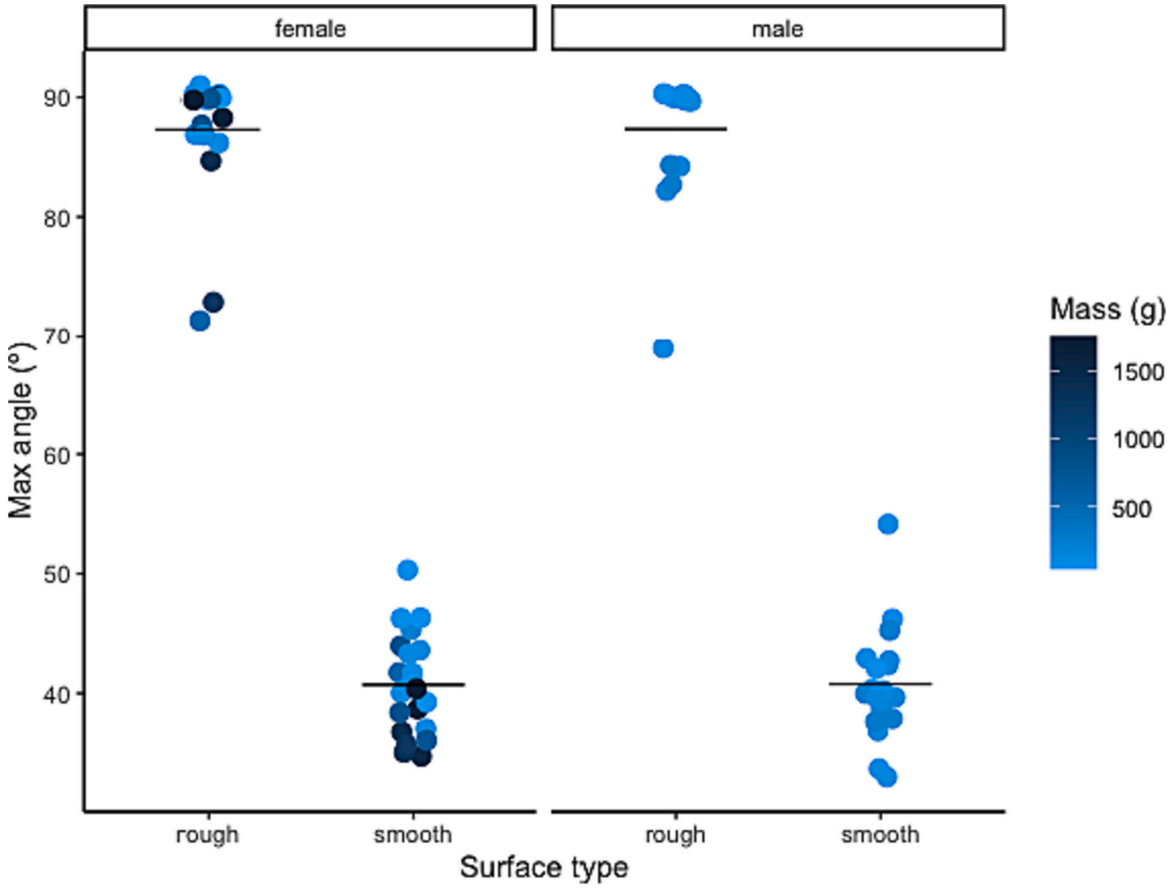

Fig. 5. The maximum clinging angle for northern map turtles with regard to smooth and rough surface types and sex with a mass gradient indicated by darker blue for larger masses and the mean for each indicated by a line. The means and standard errors for females were 87.3 +/− 1.2° on the rough ramp and 40.7 +/− 0.90° on the smooth ramp, and for males, they were 87.3 +/− 1.3° on the rough ramp and 40.8 +/− 1.1° on the smooth ramp. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

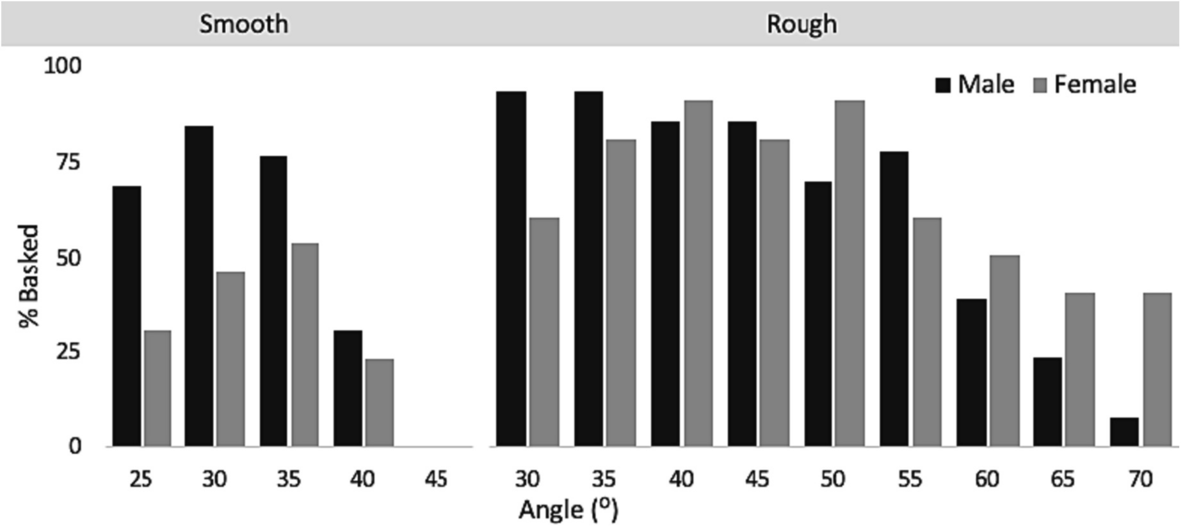

Fig. 6. The percentage of painted turtles that climbed at specific angles with regard to sex. Slopes from the smooth ramp tests ranged from 25 to 45°, and slopes from the rough ramp tests ranged from 30 to 70°.

species-specific knowledge of turtle climbing abilities should be incorporated into governmental regulations, particularly for species that are at risk.

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Author contributions

KMS, AB, GB, and SJC conceived the ideas and designed the methodology; KMS and AB collected the data; KMS and RD analysed the data; KMS and GB led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication. Funding sources were not involved in the study design; the collection, analysis, or interpretation of data; or in the writing of the report.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Steven J. Cooke reports financial support was provided by Kawartha Conservation.

Data availability

All data and R scripts are available at: doi: https://doi.org/10.6084/m9.figshare.22772141.v1

The repository has been made public.

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