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Research

Locomotion on three legs: the tripedal gaits of canine amputees

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The gaits of bipedal and quadrupedal animals are well characterized, while, with few naturally occurring tripedal gaits, little is understood regarding locomotion on three legs. Canine amputees provide a unique perturbation into the study of locomotion. This study assesses whether these individuals use distinct limb sequences, with clearly defined kinematics and kinetics, which could be considered discrete gaits. Data for a group of hind- and forelimb canine amputees across a range of speeds show that at higher speeds, three legged dogs use a three beat gallop-like gait: forelimb amputees use a rotary-like gallop; hindlimb amputees use both rotary- and transverse-like sequences. At low speeds, two strategies are observed: (i) maintenance of a three legged gallop with increased stride periods, and (ii) uncoupled walking, with an increased stride period on the 'walking' pair of legs and a constant stride period on the single leg, resulting in decoupling of fore- and hindlimb timings. The single limb is constrained by unsupported aerial time, maintaining a consistent period, striking more than once per cycle at lower speeds. Altered force distributions show high peak vertical forces in the single limb of forelimb amputees, but a relatively even distribution across all limbs in hindlimb amputees.

1. Introduction

Animal locomotion—whether terrestrial (bipedal, quadrupedal, hexapedal, etc.), arboreal (brachiation), aquatic (swimming) or aerial (flapping flight)—is often described in terms of 'gaits'. In its broadest sense, the term relates to a characteristic 'style' of locomotion: humans might be described as walking with a crouching gait, a limping gait, a rapid gait, etc. Styles of gait that relate to speed—typically walking and running in humans or walk–trot–canter–gallop in horses—are sometimes termed 'gaits'; in this context, gaits are often distinguished with discrete transitions with increasing speed [1]. Whether discontinuity in limb phasing or centre of mass (COM) kinetics is important in determining a gait depends on convention: for instance, the walk–run transition is often very blurred in many birds, whatever the metrics being used [2]. The gaits of quadrupedal animals can be distinguished in terms of their kinematics and kinetics and are related to speed, body size and body proportions. Gait selection can determine efficiency and economy of locomotion and may be limited by power, limb force and neuromuscular control. Early work by Hildebrand forms the basis of our current description of the symmetrical and asymmetric gaits of quadrupeds [3–8]. Dogs, like many other quadrupedal mammals, show symmetrical walking and trotting gaits at slower speeds, with a proportion also showing a symmetrical pacing gait [7]. At higher speeds, dogs show an asymmetric galloping gait, with both rotary and transverse limb sequences [9]. Gait selection can

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be largely understood from the perspective of work minimization [10–14], though factors such as stability and correlates with tissue stresses may play some role.

Symmetrical gaits are commonly defined using duty factor–phase relationships [5], where phase is the proportion of stride interval at which the footfall of the forefoot follows the hind on the same side, commonly expressed as a percentage. Using this convention, a 25% phase would have an even timing between each foot contact, e.g. left hind, left fore, right hind, right fore (evenly spaced in time), as is common in many quadrupedal mammalian walks [14]. A 50% phase would represent a trot, with the left forelimb striking exactly halfway through the left hind stride cycle. A perfect pacing gait, where the fore and hind on the same side of the body strike simultaneously, would be 0% (or 100%). In terms of defining gaits, the sequence of limb strikes and the relative phasing of individual limbs are key characteristics of the definitions.

There are few examples that might be considered tripedalism in nature: a number of primates will locomote tripedally periodically [15], particularly when load carrying [16]; spider monkeys can use a tripedal gait terrestrially and may use the tail as a third ‘limb’ in brachiation [17]; gibbons can locomote using three limbs if required [18]; and parrots utilize the beak as a third limb [19]. However, true tripedalism—locomotion supported by three obligate legs or feet—is limited to quadrupeds following limb loss. There is a growing population of domestic tripedal mammals in the form of canine amputees. Amputation is most commonly performed as a life-saving procedure in osteosarcoma, closely followed by trauma cases [20]. Despite this growing population, relatively little is known about the tripedal gaits of canine amputees. There have been a small number of clinically focused studies in canine amputees that demonstrate decreases in stride and stance durations and increases in duty factor when dogs locomote tripedally [21,22], as well as alterations to joint angular excursions [22,23]. In particular, hindlimb amputees are seen to move with a more retracted forelimb [24], shifting their weight more cranially and contralaterally from the amputation [21]. Increases in movement of the spine are noted in both forelimb [22] and hindlimb amputees [23]. However, the gait patterns used by these dogs remain unclear. Most notably, previous studies have not looked at a wide range of speeds, often using a single or preferred speed without indication of the limb sequences and phasing selected. In particular, the gait in a number of these studies is described as ‘trotting’ or ‘walking’; however, it is not possible to perform these symmetrical, quadrupedal gaits with only three limbs.

When using the definitions of Hildebrand [8], as above, a gait must show a ‘regularly repeating manner of moving the feet’. This regularity allows gait to be defined by the pattern and phasing of footfalls across a repeating cycle; however, it immediately excludes pathological gait, which is often characterized by irregularity of movement. In describing the grazing gait of quadrupeds, Usherwood & Smith [25] base their definition on the underlying mechanics, as per Alexander [1], and on the regular phasing of the fore–hind contact timing, but with variability in the hind–fore contact timing, allowing for aspects of regularity, as per Hildebrand, but not a single repeating cycle. Here, we begin by adopting and adapting Hildebrand’s conventions on describing gaits, maintaining an interest in how gaits might vary with speed; however, we have no *a priori* view as to whether these characteristic ‘styles’ of locomotion should show discrete transitions or be simply characterizable with cyclic criteria.

As speed increases, gait changes in relation to metabolic cost [10,26] and possibly force [27]. Increased speed is associated with increased stride lengths and stride frequencies, decreased contact times and duty factors, and greater peak vertical ground reaction forces [28–32]. Here, we do not explicitly consider COM energetics or metabolic cost. During standing and at lower speeds, the load distribution between the forelimbs and the hindlimbs of many quadrupedal, cursorial mammals is approximately 60 : 40, respectively [33–36], though this distribution may become more symmetrical at high speed [32,37]. Previous studies demonstrate significant changes to ground reaction force distribution of fore- and hindlimb amputees [21–23,38]; however, it is not demonstrated how these changes are affected by speed and whether they are dependent on gait. Further to this, some studies use simulated amputation, meaning the inertial properties of the dogs are different from those of a true amputee.

Understanding tripedalism is interesting from a biomechanics perspective as a perturbation to investigate what limits locomotion and influences gait selection. Details on the biomechanics of tripedalism can also be useful in the context of the small number of instances seen in nature, as described above. Further to this, understanding the gaits of canine amputees can play a valuable role in post-operative rehabilitation and may provide insight into assessing gait on three legs. As such, here, we investigate the limb sequences adopted by both forelimb and hindlimb amputees to distinguish any clearly defined tripedal gaits, attempting to describe these gaits via limb phasing, in line with the definitions of quadrupedal gaits. We provide trends in kinetics with increasing speed to determine how common gait parameters scale with speed in tripedal gaits.

2. Material and methods

Participants were recruited via the Royal Veterinary College’s social media and Web pages. It was required that dogs be free from any clinical condition (other than the amputation) and must be relaxed and comfortable in being handled. Studies have shown that owner satisfaction post-amputation is generally favourable and that owners consider the quality of life of amputee dogs to be good [38,39], suggesting that locomotion as part of this study did not represent anything outside of normal activity for healthy amputees. Seven forelimb amputees and six hindlimb amputees were recruited, though one forelimb amputee was excluded from the analysis owing to limited use of one of the hindlimbs; this may indicate an underlying hindlimb pathology and was not considered suitable for a study on typical healthy tripedal locomotion. Data collection took place in the Structure and Motion Laboratory at the Royal Veterinary College. Canine participants were weighed on a Kistler force platform (Kistler 9287B), and height to the withers and hip was taken with a standard tape measure (table 1).

A series of 12 mm retroreflective markers were placed, where tolerated, on the paws, joint centres and approximate body COM. Dogs were given as much time as necessary to acclimatize to the environment before performing 10–20 trials over a

Table 1. Individual subject information for the six forelimb amputees and six hindlimb amputees.

dog ID	limb amputated	reason for amputation	breed	sex	age (years)	mass (kg)	withers height (m)
dog01	left fore	car accident	mixed breed	F	6	24.5	0.60
dog02	right hind	hit by car	Staffordshire Bull Terrier	M	5	14.2	0.41
dog03	left hind	car accident	mixed breed	F	1.5	12.2	0.48
dog04	right fore	hit by car	Malinois	F	3	28.5	0.64
dog06	left hind	mast cell tumour	Golden Retriever	F	12	25.0	0.60
dog07	right hind	severe break	mixed breed	F	2.5	21.6	0.59
dog08	right fore	injury	mixed breed	M	2	28.0	0.72
dog 09	right fore	injured as puppy	Doberman	M	3	37.2	0.74
dog10	right fore	elbow fracture	Springer Spaniel	M	10	18.9	0.46
dog 11	right fore	unknown	Clumber Spaniel	M	8	25.2	0.49
dog 12	right hind	injury as puppy	Saluki	F	10	16.7	0.67
dog 13	right hind	injury as puppy	Lurcher	M	1	16.1	0.61

distance of approximately 10 m, at as great a range of speeds as possible. Treats, toys and voice were used as motivation, and dogs were not asked to exercise outside of their normal level of activity, as monitored by the owner. Twelve Qualisys cameras (Gothenburg, Sweden) collected kinematics at 250 Hz, with simultaneous video via an iPhone XR (Apple, UK) at 240 Hz, to account for trials where there was marker loss. Seven Kistler force platforms (Kistler 9287B) formed a 0.9 m by 4.2 m instrumented runway, recording three-dimensional ground reaction forces at 500 Hz.

Foot-on and foot-off frame numbers were taken from the motion analysis data, along with the average velocity of the COM marker throughout the trial. As some individuals were not comfortable with the paw markers, footfall timings for these individuals were taken from the simultaneous video. Limbs were labelled in relation to the single limb: forelimb amputees had a single forelimb (SF), ipsilateral hindlimb (IH, ipsilateral to the SF) and contralateral hindlimb (CH, contralateral to the SF); hindlimb amputees had a single hindlimb (SH), ipsilateral forelimb (IF, ipsilateral to the SH) and a contralateral forelimb (CF, contralateral to the SH). For both fore- and hindlimb amputees, the phases were initially calculated clocking by the limb contralateral to the single limb. This was then subtracted from 1 for the hindlimb amputees, to be comparable with a hind-clocked phase. This meant that the phase between the intact pair of limbs was kept apparent (50% if stepping symmetrically/walking). Figures from the data analysis were plotted in MATLAB (Mathworks, USA).

Force data were collected via Kistler Bioware and analysed in MATLAB. Individual limb stances were used in the analysis, where no other limbs were in contact with the plate during the same period. The outputs were individual limb forces in the vertical, craniocaudal and mediolateral directions throughout stance for individual dogs for each trial. Owing to variability in the horizontal forces and to focus on the mechanisms and challenges of average weight support, only the vertical forces were used in this study. Peak forces were taken to be the maximum value in vertical force during each stance and were normalized to newtons per kilogram of body mass. The ratio of forelimb to hindlimb vertical impulse was calculated for trials in which there were three consecutive individual limb stances on the plates. Vertical impulse was taken to be the integral of the vertical force curve with respect to time. Instances where both limbs of a fore- or hindlimb pair contacted the same plate were also included here. Regression lines were fitted to the force data in PAST 4 [40]. To determine whether there were significant differences in the peak forces between limbs within each group of amputees (forelimb and hindlimb), a generalized linear model was conducted in SPSS, taking speed to be a covariate and dog and leg to be fixed effects. The significance level was taken to be $p < 0.05$.

3. Results

Dogs moved through the set-up at a range of speeds from 0.9 to 6.7 m s^{-1}. Trials were excluded where the dog did not move in a straight line through the set-up or where there was an obvious change in speed. Any trials where dogs were distracted, pulling on the lead or sniffing were also removed from the analysis. Each dog achieved a minimum of 10 usable trials with multiple whole strides for each trial, varying with speed.

Limb phasing data were recorded throughout each trial (including periods not on the force plate array). Figure 1 shows individual limb period and phase data for example dogs across all trials, separated into fore- and hindlimb amputees, at a range of speeds. Subjectively, different 'gaits' were reported by the researchers and owners throughout the data collection process. Data for all individuals are shown in the electronic supplementary material.

Stride length was taken from the Qualisys data as the horizontal distance travelled by the COM marker in metres during a complete stride cycle (as defined by the paired limbs). Stride lengths ranged from 0.49 to 2.14 m and increased linearly with speed, as shown in the electronic supplementary material.

A total of 825 single limb stances were analysed from the force plate data, consisting of 199 for the SF, 113 for the CH and 117 for the IH of forelimb amputees, and 173 for the SH, 99 for the CF and 124 for the IF of the hindlimb amputees. Peak vertical ground reaction forces increased linearly with speed and are shown for individual limbs in figure 2, with representative

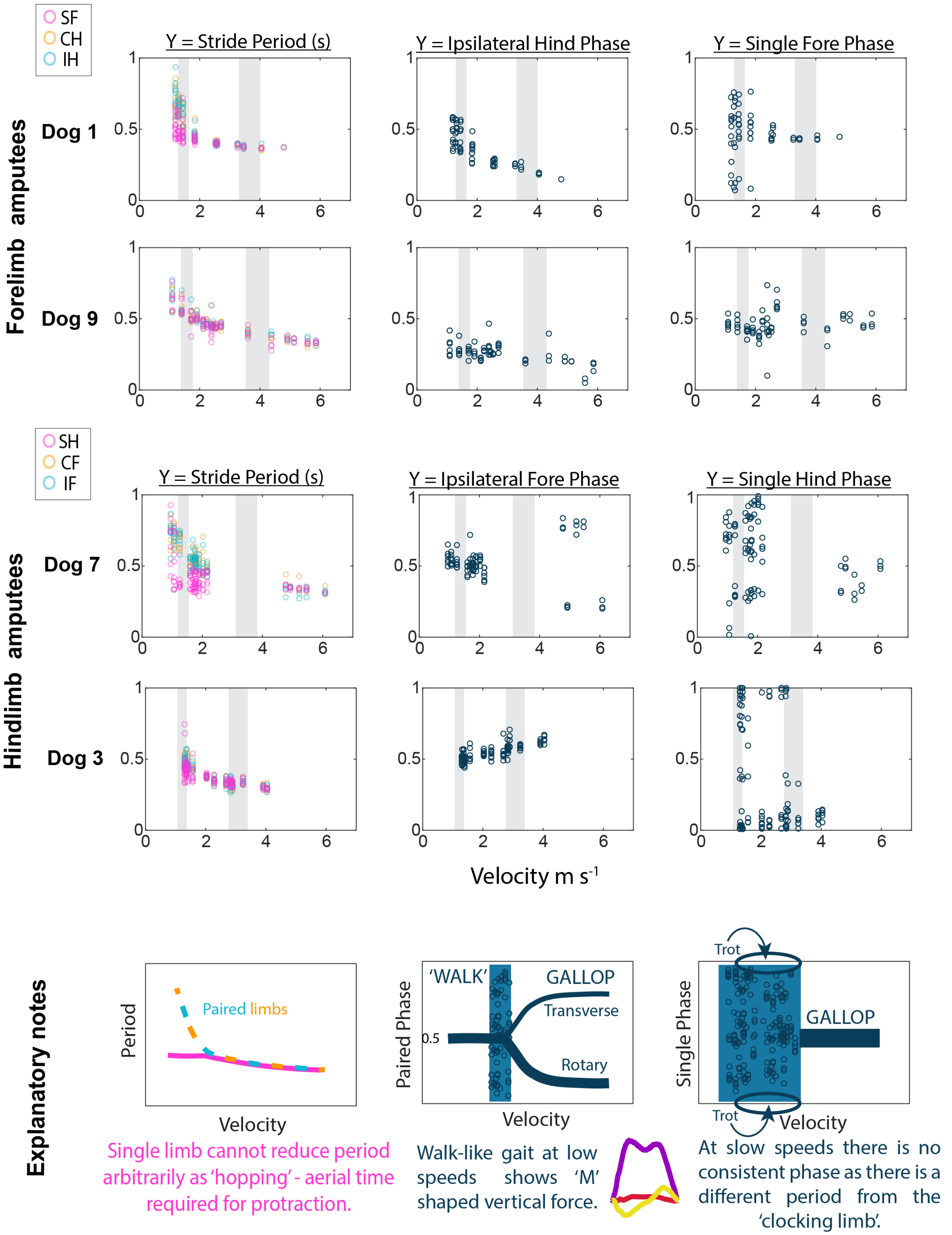

Figure 1. Individual limb period (seconds) and phase data, for representative forelimb and hindlimb amputees at a range of speeds (m s^{-1}, *x*-axis). The first column shows the contact period for the single (pink), contralateral to the single (orange) and ipsilateral to the single (green) limbs. The middle column shows the phasing of the paired limbs via the ipsilateral limb relative to the contralateral limb. The third column shows the phasing of the single limb relative to the contralateral. Phases for the hindlimb amputees are converted to be comparable with a hind-clocked phase. The grey shading represents where quadrupedal dogs of the same leg length might change gaits from walk to trot (first, Froude number 0.3–0.5) and trot to gallop (second, Froude number 2–3). Data for all individuals are shown in the electronic supplementary material. The bottom row shows how the shapes of the data represent different tripedal limb sequences. The first plot demonstrates the relatively consistent stride period of the single limb, which is constrained by unsupported air time. The second shows that a phase of 0.5 between the paired limbs demonstrates a walk-like gait, while at increased speed, the rotary and transverse gallop sequences can be identified by the phasing of the intact pair. The final section demonstrates that there is no consistent phasing between the single limb and the contralateral owing to the differing frequencies, with the single limb striking more than once per cycle. With increasing speed, the single limb does only strike once per cycle.

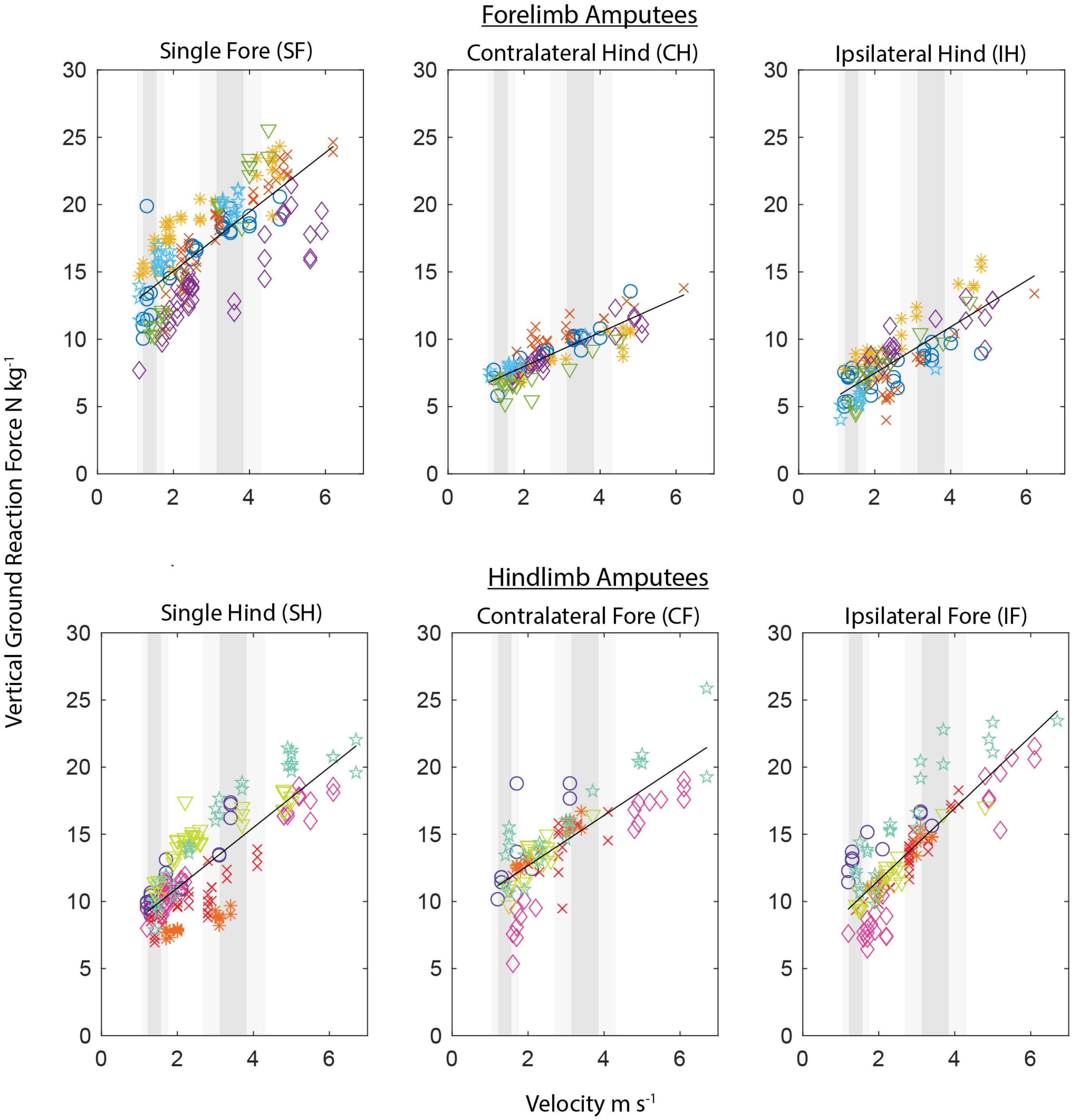

Figure 2. Peak vertical limb force data (N kg^{-1}) for individual foot strikes in forelimb (top row) and hindlimb (bottom row) amputees, against speed (m s^{-1}). Different marker/colour combinations represent individual dogs. The grey shading represents where quadrupedal dogs of the same leg length might change gaits from walk to trot (first, Froude number 0.3–0.5) and trot to gallop (second, Froude number 2–3). The data consist of 429 individual foot strikes across 99 trials for six dogs in the forelimb amputee data and 396 individual foot strikes across 79 trials for six dogs in the hindlimb amputee data. Line equations: SF $y = 2.204x + 10.643$ ($r^2 = 0.562$); CH $y = 1.264x + 5.452$ ($r^2 = 0.703$); IH $y = 1.721x + 4.035$ ($r^2 = 0.620$); SH $y = 2.249x + 6.511$ ($r^2 = 0.644$); CF $y = 1.871x + 8.923$ ($r^2 = 0.597$); IF $y = 2.680x + 6.218$ ($r^2 = 0.685$).

trials for the different ‘gaits’ shown in figure 3. Peak vertical force was significantly higher in the SF of forelimb amputees compared with the remaining hindlimbs, while peak vertical force in the SH of hindlimb amputees was significantly lower when compared with the remaining forelimbs. Cranio-caudal and medio-lateral forces were highly variable and were not used in the analysis.

Forelimb amputees supported 52 ± 4% (mean ± standard deviation) of the total load on their remaining forelimb, while hindlimb amputees supported 30 ± 5% on their remaining hindlimb during locomotion, though this front:back impulse distribution varied with speed and is shown in figure 4. (Note that these values may be invalid for some dogs at low speeds where cyclic gaits were not observed, and no valid definition of stride period was possible—see §4.)

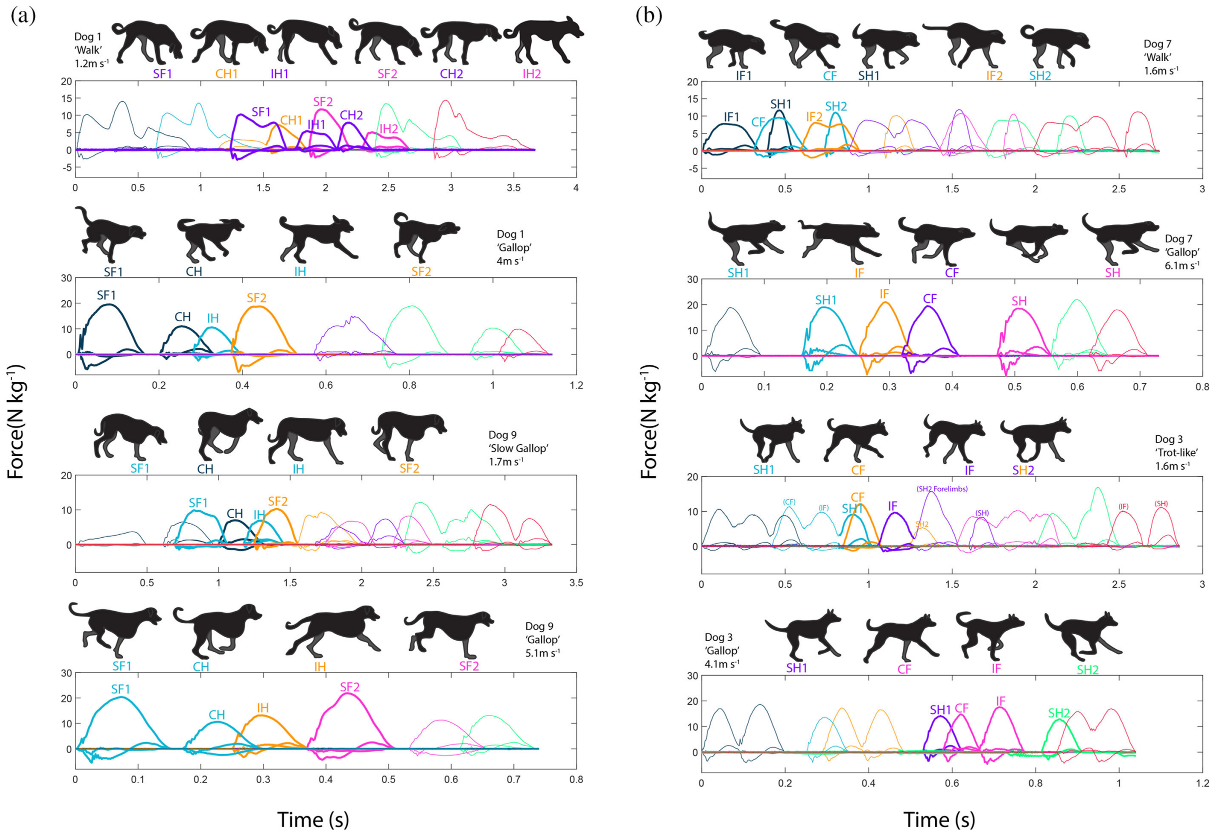

Figure 3. Example raw force data of representative trials for forelimb (a) and hindlimb (b) amputees using different tripedal limb sequences. Data show three-dimensional forces (N kg^{-1}) against time (seconds) for single trials, with different colours representing individual force plates. Foot strikes highlighted in bold correspond to whole strides, illustrated by the silhouettes above.

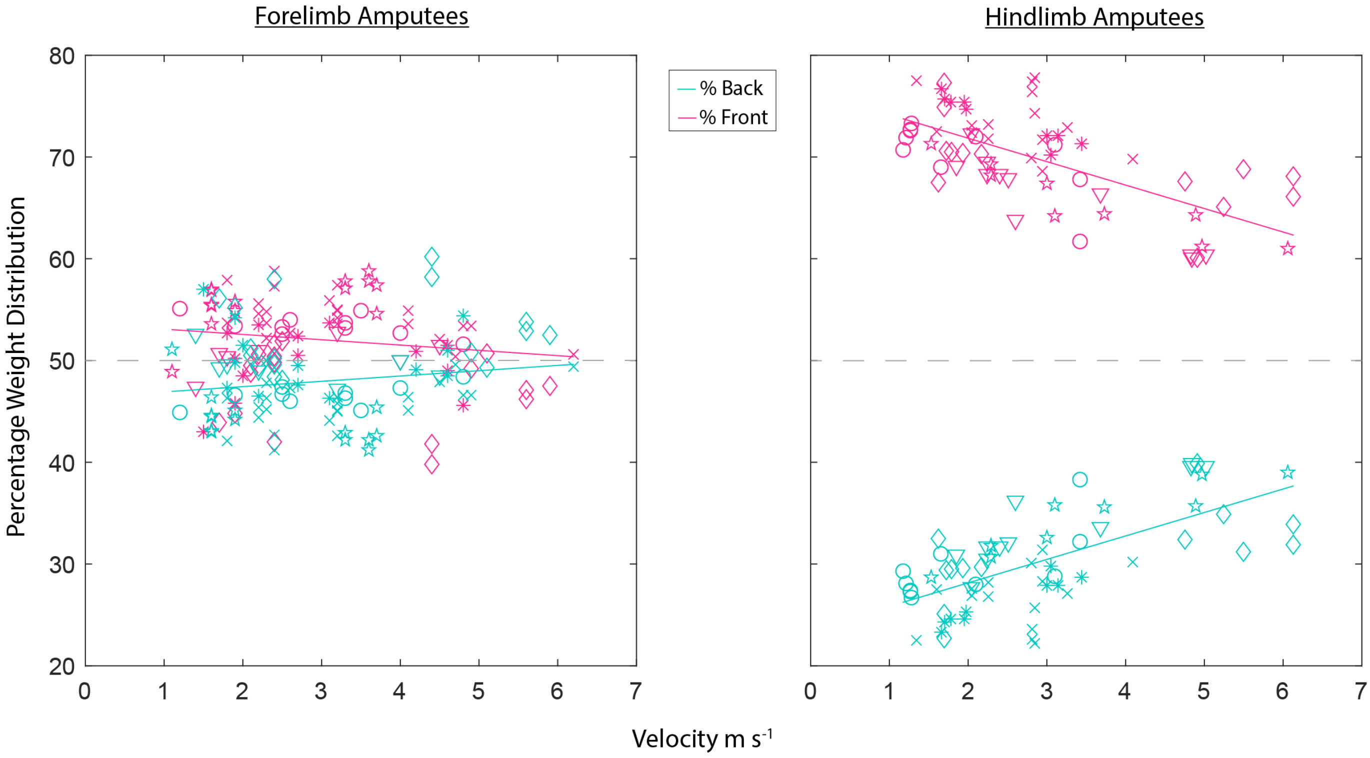

Figure 4. Front : back impulse distribution (%) for forelimb and hindlimb amputees. Pink shows total forelimb impulse, and blue shows total hindlimb impulse with speed (m s^{-1}). Data consist of 86 whole strides worth of data across six dogs for the forelimb amputee data and 67 whole strides worth of data across six dogs for the hindlimb amputee data. Different markers represent individual dogs. Line equations: forelimb amputees: front $y = -0.521x + 53.607$ ($r^2 = 0.026$); back $y = 0.521x + 46.393$ ($r^2 = 0.026$); hindlimb amputees: front $y = -2.305x + 76.46$ ($r^2 = 0.441$); back $y = 2.305x + 23.54$ ($r^2 = 0.441$).

4. Discussion

In previous studies, the gait used by forelimb amputees is described as random and as a 'blend of characteristics associated with other clearly defined gait patterns' [22]. Here, we find that—while sometimes not fitting within Hildebrand's paradigm of gait descriptions—none of the gaits needs to be considered random. Broadly apparent in dogs 1, 3, 7, 8, 12 and 13, there is a low speed where the stride period of the intact pair of limbs increases above that of the single limb. At these low speeds, the intact limb pair 'walks' (50% left–right–left) and the single limb has a different period, making the hind–fore phasing change every stride. The periods of the two legs of the intact pair match up, so a fairly consistent phase is maintained for the ipsilateral limb. When there is a mismatch in period between the single limb (which cannot 'walk') and the pair (which can 'walk'), this becomes apparent in the noise in phase for the single limb. This walk-like gait means that the single limb strikes more than once per stride cycle, so duty factors were not calculated owing to the lack of a consistent cycle. While the decoupling between paired and single limb cycles gives the impression of a discoordinated 'random' gait, it presumably has the advantage that the single limb need not be driven excessively rapidly and/or the period and vertical deflections of the body motion need not be high (if the single limb cannot be driven sufficiently quickly). Anecdotally, all dogs were reluctant to move at these very slow speeds, and the gait appeared laboured. Dogs that did not perform this walk-like gait during the data collection process did appear to show a similar gait during slow browsing in between trials, but this was always at an inconsistent speed for brief periods. This can be likened to the grazing gaits of quadrupeds [25].

The alternative strategy to this tripedal walk was a slow gallop-like gait where the limbs followed the same sequence as at higher speeds (described below) but with extended contact times and no aerial phase. This slow gallop gait shows coupled fore/hind movement with a single limb striking once per cycle. The disadvantage to this strategy is presumably that the period has to be relatively high in order to provide time for the single limb to swing forward between stances and—given a walking, striding stance is impossible in the single limb—either the whole body must 'bounce' with a large vertical deflection or all of the limbs must be driven at an increased frequency, either of which would be costly.

At intermediate speeds, hindlimb amputees showed a trot-like gait where the single hind and contralateral fore moved together. Forelimb amputees loosely showed a pace-like gait where the single forelimb and ipsilateral hindlimb moved approximately together. At higher speeds, all legs achieve the same, lower stride period, resulting in a gallop-like pattern for all limbs. Both transverse-like and rotary-like sequences were seen in hindlimb amputees, while only a rotary-like pattern was seen in forelimb amputees.

The above gaits can be seen in the shapes of the plots in figure 1, which is extended to include all individuals in the electronic supplementary material. The first column demonstrates the relatively consistent stride period of the single limb, which is constrained by unsupported air time, resulting in the two slow strategies observed. The second shows that a phase of 0.5 between the paired limbs demonstrates a walk-like gait, while at increased speed the rotary and transverse gallop sequences can be identified by the phasing of the intact pair. The final column demonstrates that there is no consistent phasing between the single limb and the contralateral owing to the differing frequencies, with the single limb striking more than once per cycle, shown as a wide scatter. With increasing speed, the single limb does only strike once per cycle, reducing this scatter. The trot-like gait can also be seen in the third column, where the phase of the single limb and contralateral limb 'match' (0 and 100%), though the pace-like gait is not seen as the phasing between the single and the ipsilateral is not shown.

The redistribution of vertical impulse and peak vertical force differs between fore- and hindlimb amputees. In hindlimb amputees, the peak vertical force was lower in the SH than in the remaining forelimbs. While all limbs consequently take a slightly higher percentage of the total body weight than they did pre-amputation, the total body weight itself is, by nature, less post-amputation. In forelimb amputees, the remaining forelimb bears more of the overall weight than the hindlimbs, around 50%, and could therefore be prone to resultant degeneration owing to increased and more frequent loading, seen in previous studies as increased hyperextension of the carpus in stance [22].

The redistribution of load in amputees is consistent with a foreweight bias, whereby removal of a limb makes the peak force in the remaining forelimb of forelimb amputees more extreme, whereas in hindlimb amputees, it makes the distribution across the remaining limbs more even, also demonstrated in previous studies [38]. Forelimb amputees supported 52 ± 4% (mean ± standard deviation) of the total load on their remaining forelimb, while hindlimb amputees supported 30 ± 5% on their remaining hindlimb. During locomotion, this front–back impulse distribution varied with speed and is shown in figure 4. This adjustment from the normal 60% forelimb, 40% hindlimb impulse distribution [36] is not surprising: removing a leg removes a considerable mass and thus demands less weight support from the respective girdle. This reasoning can be extended to a crude quantitative calculation of the amputated leg masses, assuming no postural adjustments, prior to leg removal. If an entire four legged dog is composed of two hind leg masses MHL, one hind body portion mass MH, two fore leg masses MFL and one forebody portion mass MF, the complete body mass supported by all legs of a four legged dog is—as a proportion—given by

$$1 = \mathrm{MH} + 2\mathrm{MHL} + \mathrm{MF} + 2\mathrm{MFL}\,.$$

The proportion of body weight taken by only forelimbs in a four legged dog, p, is

$$p = (\mathrm{MF} + 2\mathrm{MFL})/(\mathrm{MF} + 2\mathrm{MFL} + \mathrm{MH} + 2\mathrm{MHL})\,.$$

The proportion of weight supported by the front legs in a front-leg amputee dog p_{Famp} is

$$p_{\mathrm{Famp}} = (\mathrm{MF} + 1\mathrm{MFL})/(\mathrm{MF} + 1\mathrm{MFL} + \mathrm{MH} + 2\mathrm{MHL})\,.$$

The proportion of weight supported by the hind legs in a hind leg amputee dog p_{Hamp} is

$$p_{\mathrm{Hamp}} = (\mathrm{MH} + 1\mathrm{MHL})/(\mathrm{MF} + 2\mathrm{MFL} + \mathrm{MH} + 1\mathrm{MHL})\,.$$

Solving these simultaneous equations gives

$$\mathrm{MFL} = \frac{p_{\mathrm{Famp}} - p}{p_{\mathrm{Famp}} - 1}$$

and

$$\mathrm{MHL} = \frac{p + p_{\mathrm{Hamp}} - 1}{p_{\mathrm{Hamp}} - 1}\,.$$

With the values reported here of $p_{\mathrm{Famp}} = 0.52$ and $p_{\mathrm{Hamp}} = 0.3$, each removed forelimb would have weighed 16.7% of complete body weight, and each hindlimb 14.2% of complete body weight. While the true amputated leg mass values are unknown, these values suggest that the simplest explanation of changes in fore/hind loading is not unreasonable. However, active kinematic or postural compensation of fore/hind weight would not be unexpected. In the previous literature, it is seen that hindlimb amputees move with a more retracted forelimb posture and increased anteversion of the pelvis [24], with an increased degree of pitching [21], likely affecting the role of the limbs in terms of accelerating/braking [41,42]. Forelimb amputees have shown extended head and neck positions combined with increased lumbosacral flexion [22]. As such, load distribution that balances pitch demand may be due to motions of the COM and horizontal forces, though we only focus on vertical forces here. These changes in posture suggest changes in COM position, not a fixed point to begin with, alongside the changes to load distribution associated with speed, seen in the literature [32,37] and this study. While the above calculations do not account for such shifts in COM position and therefore cannot provide the whole answer, they provide a suitable starting point in explaining the shifts in load distribution seen.

While the peak vertical forces seen at maximum speed here do not exceed those seen in galloping quadrupedal dogs [41], they do occur at much lower speeds and could therefore be indicative of a force limit to the maximum speed of amputees. While peak vertical forces were lower at lower speeds, at the walk-like gait the single limb strikes more frequently than once per stride; so, the limb is loaded more frequently. It was apparent that this was not a preferred speed for any of the dogs and appeared laborious, potentially owing to the awkwardness of the phasing or the frequent loading of the single limb. Given that there were distinct alternative gait strategies at slow speeds, this could indicate that such speeds were uncomfortable, similar to those around the human walk–run transition speed. This was most apparent in the forelimb amputees. It is worth considering this during post-operative rehabilitation, and potentially not walking dogs too slowly, but aiming for a more comfortable middle speed. With regard to the rehabilitation of canine amputees, in particular physiotherapeutic intervention, this study establishes a methodology for assessing locomotion on three legs.

To conclude, a range of speed-dependent ‘gaits’ is described for tripedal dogs. Gaits at higher speeds are cyclic, with kinematic equivalents and apparent kinetic similarities to quadrupedal gaits, particularly transverse and rotary galloping. At low speeds, either low-speed versions of the high-speed gaits are adopted, but with high stride periods, or a decoupled fore–hind walk–hop gait is observed, both with—subjectively—a high mechanical effort. This decoupled gait does not fit within the classical quadrupedal gait definitions, and a consistent timing relationship between leg motions cannot be described; however, it does appear to be a consistent and understandable locomotory style naturally adopted by dogs after limb loss. This work establishes a methodology to begin assessing gaits in canine amputees, essential for post-surgical rehabilitation. Further to this, there are implications in the field of biologically inspired robots, which are rapidly advancing with regard to bipedal, quadrupedal and hexapedal legged locomotion [43], with designs becoming increasingly capable of compensating for limb loss [44,45]. Data presented in this study contribute to the understanding of locomotion, specifically gait patterns, on three legs and add valuable insight into how quadrupedal systems can compensate on three legs.

Ethics. Ethical approval for this study was granted by the Royal Veterinary College (RVC) Welfare and Ethics Committee (URN 2019 1894-3).

Data accessibility. Data for this paper are provided via the electronic supplementary material, available online [46].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors’ contributions. Z.T.S.D.: conceptualization, data curation, formal analysis, methodology, project administration, writing—original draft, writing—review and editing; A.L.S.: data curation, formal analysis, methodology, writing—original draft; J.R.U.: conceptualization, formal analysis, funding acquisition, investigation, supervision, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed herein.

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