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Recreational runners with Achilles tendinopathy have symmetrical single leg hopping mechanics, and contact duration is associated with vertical stiffness

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Abstract

Background Runners with unilateral Achilles tendinopathy (AT) may exhibit inter-limb differences in lower limb mechanics during single leg hopping, and clinic friendly temporospatial measures may relate to stiffness characteristics.

Objective To test whether runners with unilateral AT have symmetrical lower limb mechanics across during hopping, and to examine the association between contact duration and stiffness.

Design Within-subject study.

Method Seventeen recreational runners with unilateral AT performed single leg hopping tasks: self-selected cadence (20 s), maximal height hopping (≥ 3 consecutive hops), cued hopping at 132 hops·min^{-1} (20 s), and a progressive test at 120, 108, and 96 hops·min^{-1} (15 hops each). Inter-limb comparisons evaluated temporospatial variables, kinematics, kinetics, and stiffness (vertical, leg, joint). When no inter-limb differences were detected for a variable within a task, a participant level, pooled value (mean of both sides) was calculated. Pearson correlations examined the associations between contact duration and stiffness at the participant level.

Results No inter-limb differences were observed for vertical or leg stiffness, ankle mechanics, or temporospatial variables across tasks. Small differences were observed at the hip and knee (e.g., greater hip flexion angle by 1–3° at 120 and 108 hops·min^{-1}, $p = 0.02$; greater knee flexion by 3° during maximal height hopping, $p = 0.02$), and greater peak hip power on the affected side at 120 hops·min^{-1} (0.82 (0.38) vs. 0.58 (0.33) W·kg^{-1}, $p = 0.03$). Contact duration was strongly and negatively associated with vertical and leg stiffness during self-selected hopping ($r = -0.86$ and -0.85), and with ankle stiffness ($r = -0.74$).

Conclusion Recreational runners with unilateral AT, had symmetrical lower limb mechanics during single leg hopping tasks, with subtle proximal differences of uncertain clinical relevance. The strong association between contact duration and stiffness supports the clinical utility of temporospatial metrics during self-selected hopping as practical indicators of lower limb mechanical behaviour.

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Keywords Single-leg hop test, Rehabilitation, Hopping functional capacity

Background

Mid-portion Achilles tendinopathy (AT) is characterised by persistent pain and functional limitations [1, 2], affecting up to 10% of recreational runners [3]. AT often leads to reduced participation in running, with one in four runners reporting a reduction in their running distance within the first 12 months of experiencing symptoms [4]. Returning to running is a key rehabilitation milestone [5], yet outcomes vary [2], and symptoms may persist despite intervention [6, 7]. Although pain is the primary complaint, altered lower limb mechanical function may influence recovery [8, 9].

Repetitive, high-load activities such as running, jumping, and hopping rely on the storage and release of elastic energy in the calf muscle-tendon complex [10–13]. In AT, this mechanism may be impaired [14], which reduces the ability of the tendon to tolerate load [15]. Individuals with AT may adopt compensatory movement strategies, such as reduced ankle dorsiflexion and knee flexion during high-load tasks to redistribute mechanical demand [16]. These adaptations may help manage pain, however, may compromise the ability of muscles to store and release elastic energy [17, 18]. Lower limb stiffness, including vertical, leg, and joint stiffness, describes how the limb can modulate movement of the joints in response to the muscular forces being exerted to control the joints [10–13, 19]. The aim of muscle-tendon units are to resist deformation and optimise elastic energy during loading [11, 13], therefore optimal stiffness is task and context dependent [20, 21], while compensatory strategies may coexist with relatively high or low stiffness [22, 23].

Recent work has demonstrated that AT is associated with marked morphological and mechanical asymmetries at the tendon [24]. AT tendons show increased cross-sectional area, altered material properties, and increased vascularity compared with the contralateral side [24], although asymmetry in functional performance does not always correspond to these structural differences. Research examining whole body movement also shows that, despite structural changes, some individuals with AT maintain symmetrical walking ground reaction forces and muscle synergies [25]. These findings suggest that asymmetry in AT is task dependent, and that tasks with higher mechanical demand may be more sensitive in detecting meaningful functional differences. Clinically, dynamic tests such as single-leg hopping may capture mechanical characteristics that better reflect the forces experienced by joints and the Achilles tendon during running [26, 27]. Consensus guidelines recommend assessing physical function capacity in people with tendinopathy, such as hopping performance [28]. Pain during single-leg hopping is also a recommended as being a tendon specific load test, with the potential to provide information distinct from traditional questionnaires such as the VISA-A [29]. However, most published studies have examined self-reported pain during hopping rather than the biomechanical characteristics [30, 31]. Further, few studies have evaluated hopping biomechanics in recreational runners with AT and the published studies have reported conflicting results related to asymmetry between sides during dynamic tasks [25, 27]. Therefore, it remains unclear whether there are functionally relevant asymmetries between sides in runners with AT.

Single leg hopping provides a clinically feasible, high load task that challenges lower limb mechanical behaviour relevant to running and which can be performed in a controlled environment [32]. Because contact duration varies systematically with lower limb stiffness [33, 34], it may serve as a practical surrogate when full biomechanical analysis is not available as it can be easily measured using relatively low-cost equipment [35]. Understanding whether hopping mechanics differ between symptomatic and asymptomatic limbs, and whether contact duration relates to stiffness, may help clarify the clinical utility of hopping tasks in AT assessment.

The purpose of this study was to (1) test whether runners with unilateral AT exhibit side to side symmetry in lower limb stiffness, kinematics, and kinetics during single leg hopping tasks of different efforts; and (2) examine associations between contact duration and stiffness (vertical, leg, ankle) to inform the potential clinical use of temporospatial metrics.

Methods

Study design

This was a within-subject study.

Participant recruitment and eligibility

Participants were recruited via physiotherapy/medical clinics and online advertisements (e.g., local running clubs, social media). Eligibility screening was completed online, followed by a brief video call to confirm details and answer questions. Eligible participants were invited to the laboratory for a single testing session after providing written informed consent.

Inclusion criteria were aged 18–55 years; unilateral mid portion AT symptoms for > 12 weeks; participation in running at least twice per week for the preceding 6 months with no minimum weekly distance imposed; and sufficient English language proficiency to provide informed consent. Exclusion criteria were prior Achilles tendon rupture/surgery; current exercise intervention

for AT; inflammatory, metabolic, or neurological conditions; prior lower limb surgery; and non mid portion Achilles pathologies. A series of tests were performed to determine load-related pain (three repetitions per side) including: double-leg and single-leg calf raises on a flat surface, single-leg calf raises on the edge of a step and on-the-spot single-leg hopping [36]. We diagnosed mid-portion AT clinically based on site of pain and palpation [37], and used ultrasound (Artus Probe: L15-7H40-A5, Telemed Echo Wave 2, version 4.1.1) to confirm diagnosis. People with other primary diagnoses (insertional AT, retrocalcaneal bursitis, plantaris tendinopathy, and isolated paratenonitis) were excluded [38].

Height, body mass, and leg dominance (preferred kicking leg) [39] were recorded and the VISA A (functional status) [40], Tampa Scale for Kinesiophobia (movement related fear) [41] questionnaires were completed with report of pain (Numerical Pain Rating Scale (NPRS)) for current the 7 day and 3-months prior to testing, and the self-reported weekly running distance for 6 months prior to testing. These characteristics provided a profile for each participant.

A moderate effect size (d = 0.5) was used for the sample size calculation, based on findings from earlier studies that investigated vertical stiffness in runners [42]. A power of 80% and an alpha level of 0.05 was used such that the required sample size was 15 participants (G*Power Version 3.1.9.6).

The study was performed in accordance with the Declaration of Helsinki and was approved by the Monash University Human Research Ethics Committee (Project ID: 17888).

Instrumentation and participant preparation

Thirty retroreflective markers (7 mm in diameter) were adhered to the skin overlying anatomical landmarks of the pelvis and lower limbs in accordance with the Rizzoli lower body marker template [43]. An eight-camera OptiTrak Motion analysis system (Natural Point, Corvallis, OR, USA) sampling at 240 Hz was synchronised with a force plate (400 × 600 mm) (AMTI Inc., Watertown, MA) sampling at 1200 Hz, to synchronously collect marker and force plate data (Motive v2.3.1, OptiTrak, Natural Point, Corvallis, OR, USA).

Table 1 Testing parameters for on-the-spot single-leg hopping tasks

Task	Task parameters
Self-Selected cadence	20 s
Maximal effort	5 hops
132 hops.min^{-1}	20 s
Progressive hop test	15 hops each at 120, 108, and 96 hops.min^{-1} (45 total continuous hops)

Testing procedure

Participants performed a standardised warm-up consisting of straight and bent knee single-leg calf raises (x3 each), continuous single-leg, vertical hops (x3), and seated submaximal to maximal isometric calf muscle contractions of 3–5 s duration (x5) on each side. Participants then performed: (i) self-selected cadence hopping (20 s), (ii) maximal height hopping (≥ 3 consecutive hops), (iii) cued hopping at 132 hops·min^{-1} (20 s), and (iv) a progressive test at 120, 108, and 96 hops·min^{-1} (15 consecutive hops at each cadence) (Table 1). Cueing (audio visual metronome) was used only for the 132 hops·min^{-1} and progressive tests and cadence was measured post hoc. Cueing was provided by a custom-built audio-visual metronome (Matlab, Version 23.2) with a computer monitor (Dell: Pro 24 inch Plus QHD USB-C Hub Monitor) placed in front of the participant at eye level. Participants were instructed to land on the synchronous audible tone and visual signal.

Participants were instructed to avoid letting their heel touch the ground and to keep their arms crossed over the chest to minimise arm movement for each task. Prior to each task, participants completed a familiarisation period of each task consisting of 5 consecutive hops followed by completion of the task, in a fixed order (Table 1) with each test repeated on both sides in a random order (coin toss), to reduce an order effect. To reduce fatigue effects, there was a 3-minute rest period between test efforts.

Data processing

Motion-capture and force-plate data were exported as C3D files (Motive v2.3.1, OptiTrak, Natural Point, Corvallis, OR, USA) and processed in Visual3D (v6.01.36, C-motion Inc., Rockville, MD). Marker trajectories and force-plate signals were low-pass filtered using a 10 Hz fourth-order Butterworth filter to reduce high-frequency noise [44]. Gaps in marker trajectories up to 25 frames were filled using linear interpolation [44].

Initial contact (IC) was defined as the first frame in which vertical ground reaction force (vGRF) was ≥ 10 N [45]. Mid-stance (MS) was defined as the frame of peak vGRF. Toe-off (TO) was defined as the frame in which vGRF last exceeded 10 N. A hop cycle was defined from IC to the subsequent IC. The loading phase was from IC to peak vGRF, and the propulsion phase was from peak vGRF to TO.

Sagittal-plane joint angles were extracted at IC, MS, and TO, and used to calculate joint excursions. Joint moments were normalised to body mass (N·m·kg^{-1}). Joint stiffness (N·m·kg^{1}·rad^{1}), and joint power (W·kg^{1}) was calculated over the loading phase. Vertical

stiffness was calculated as peak vGRF divided by the centre-of-mass vertical displacement from IC to peak vGRF [46]. Leg stiffness was calculated as peak vGRF divided by the change in leg length (hip-joint centre to centre of pressure) over the same interval [46].

For each hopping task, three consecutive hop cycles were selected from the middle third of the trial. For cued tasks, cycles were required to fall within ± 5% of the target cadence. For self-selected cadence hopping, cycles within ± 5% of the mean of 15 hop cycles was used. For maximal-height hopping, we selected three consecutive cycles with steady cadence closest to the mode of the block were selected. Mean and standard deviation values were then calculated across the three cycles for each variable.

Statistical analyses

All statistical tests were performed in statistical software (GraphPad Prism V10.4.1, Boston, Massachusetts, US). Paired t tests compared affected vs. unaffected sides within each task. When no inter-limb difference was detected for a variable within a task, the score for each side were pooled (mean of both sides), reflecting symmetry between sides and this score was used for subsequent analyses. Pearson correlations evaluated associations between contact duration and vertical, leg, and ankle stiffness at the participant level. Correlations were treated as exploratory given $N = 17$; 95% CIs are reported to convey precision.

Results

Of the 19 participants who completed the testing procedure, data from two participants could not be analysed due to signal loss of pelvic markers and the force plate.

Table 2 Participant profile and clinical examination findings. Mean (SD)

Age (years)	36.4 (11.5)
Height (m)	1.70 (0.08)
Body Mass (kg)	68.5 (12.2)
Body Mass Index ($kg{\cdot}m^{-2}$)	23.7 (2.5)
Victorian Institute of Sport Assessment (score out of 100)	70 (16)
TAMPA scale for kinesiophobia 17 (score out of 68)	32 (4)
Pain past 24 h (Numerical Pain Rating Scale (NPRS))	3.3 (2.0)
Pain past 7 days (NPRS)	4.1 (2.4)
Pain past 3 months (NPRS)	4.2 (2.2)
Running past 6 months (km/week)	32.8 (22.4)
Running past 12 months (km/week)	30.2 (20.1)

Therefore, the final analysis included data from 17 participants ($N = 17$, 9 men and 8 women) (Table 2). Seven participants reported a history of tendon-related pain at other sites, including the elbow ($n = 2$), hamstring ($n = 5$), and gluteus medius ($n = 1$).

Stiffness

There were no significant differences in vertical stiffness ($p \geq 0.07$), leg stiffness ($p \geq 0.09$), or ankle joint stiffness ($p \geq 0.52$) between the affected and unaffected sides during any of the hopping tasks (Table 3).

Temporospatial characteristics

There were no significant differences between sides for temporospatial characteristics, including contact time ($p \geq 0.10$), flight time ($p \geq 0.46$), cadence ($p \geq 0.08$), loading duration ($p \geq 0.18$), propulsion duration ($p \geq 0.08$), hop height ($p \geq 0.26$), hop duration ($p \geq 0.14$) during any of the hop tasks.

Table 3 Dependent variables (mean (SD)) including vertical ground reaction force (multiples of body weight), and vertical, leg and joint stiffness at each cadence for affected and unaffected sides

		Self-Selected	132 hops.min^{-1}	Max hop	Progressive hop test (hops.min^{-1})		
					120	108	96
Cadence (hops.min^{-1})	AT	129 (14.9)	133 (2.9)	95 (12.8)	121 (1.9)	109 (5.9)	99 (8.9)
	Control	126 (14.1)	132 (2.5)	90 (15.6)	121 (1.7)	108 (4.9)	97 (3.3)
vGRF max (BM)	AT	2.5 (0.39)	2.5 (0.28)	2.6 (0.45)	2.3 (0.30)	2.1 (0.37)	2.0 (0.35)
	Control	2.5 (0.35)	2.6 (0.27)	2.6 (0.31)	2.3 (0.32)	2.1 (0.38)	1.9 (0.23)
Vertical Stiffness (kN.m^{-1})	AT	24.6 (7.5)	27.1 (9.0)	18.5 (5.1)	21.7 (11.1)	18.9 (7.4)	17.7 (7.4)
	Control	23.9 (7.7)	26.7 (7.9)	18.7 (4.6)	19.9 (5.5)	16.5 (3.3)	15.6 (3.0)
Leg stiffness (kN.m^{-1})	AT	25.6 (7.6)	27.8 (8.5)	19.1 (5.4)	22.5 (10.4)	19.8 (7.3)	18.4 (7.5)
	Control	24.9 (8.1)	28.0 (8.2)	19.7 (4.9)	21.4 (5.7)	17.7 (3.6)	16.7 (3.4)
Ankle Joint stiffness (N.m.rad^{-1})	AT	5.9 (1.5)	6.5 (1.3)	4.6 (1.5)	5.3 (1.5)	4.6 (1.3)	4.2 (1.4)
	Control	6.0 (1.4)	6.4 (1.1)	4.5 (1.5)	5.2 (1.1)	4.5 (1.0)	4.1 (0.9)
Knee Joint stiffness (N.m.rad^{-1})	AT	6.8 (2.0)	7.3 (1.4)	5.9 (2.4)	6.1 (1.4)	5.3 (1.4)	4.2 (1.5)
	Control	7.0 (3.5)	7.5 (1.3)	5.4 (2.0)	6.5 (1.5)	5.4 (1.7)	3.9 (0.8)
Hip Joint stiffness (N.m.rad^{-1})	AT	9.9 (18.7)	11.9 (20.9)	9.8 (9.5)	6.8 (9.6)	8.9 (14.1)	6.4 (8.9)
	Control	10.4 (12.3)	14.6 (23.2)	10 (9.4)	10.7 (23.3)	7.2 (7.6)	5.9 (6.1)

VGRF max Vertical ground reaction force maximum (normalised to body mass (BM)), *ms* millisecond, *bpm* beats per minute

Table 4 Correlation coefficients (mean (95%CI) between contact time and stiffness (vertical, leg and ankle joint) for each hopping task

	Vertical Stiffness	Leg Stiffness	Ankle Stiffness
Self-selected hopping	-0.86 (-0.95 to -0.66)	-0.85 (-0.95 to -0.63)	-0.74 (-0.90 to -0.41)
132 hops.min^{-1}	-0.79 (-0.92 to -0.50)	-0.81 (-0.93 to -0.54)	-0.44 (-0.76 to -0.05)
Max hopping	-0.66 (-0.87 to -0.26)	-0.66 (-0.87 to -0.27)	-0.6 (-0.84 to -0.17)
PHT at 120 hops.min^{-1}	-0.65 (-0.86 to -0.24)	-0.64 (-0.86 to -0.23)	-0.54 (-0.81 to -0.074)
PHT at 108 hops.min^{-1}	-0.53 (-0.81 to -0.07)	-0.54 (-0.81 to -0.083)	-0.49 (-0.78 to -0.01)
PHT at 96 hops.min^{-1}	-0.32 (-0.69 to 0.19)	-0.36 (-0.72 to 0.15)	-0.37 (-0.72 to 0.13)

PHT Progressive hop test

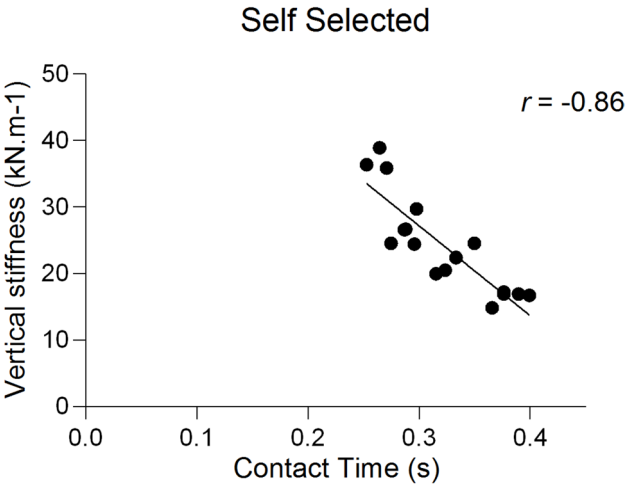


Fig. 1 Correlation between contact time and vertical stiffness during self-selected hopping

Kinematics

Peak hip flexion angle (joint angles are in degrees, values are mean (SD)) was greater on the affected side (27° (7)) compared with the unaffected side (24° (8)) during the progressive hop test at 120 hops.min^{-1}, and at 108 hops.min^{-1} (30° (8) vs. 28° (8)) ($p = 0.02$). Hip flexion angle at mid-stance was greater on the affected side (26° (7)) compared with the unaffected side (23° (7)) during the progressive hop test at 120 hops.min^{-1}, and at 108 hops.min^{-1} (28° (8)) vs. 27° (7)) ($p = 0.02$). Hip flexion angle at TO was greater on the affected side (18° (10)) compared to the unaffected side (15° (7)) ($p = 0.02$) during the progressive hop test at 120 hops.min^{-1}. Knee flexion angle was greater on the affected side (48° (6)) compared with the unaffected side (45° (7)) ($p = 0.02$) during the maximal height hop test. There were no significant differences between sides for all other kinematic characteristics (Supplementary File 3).

Kinetics

Peak hip joint power (W·kg^{-1}, mean (SD)) during the loading phase was greater on the affected side (0.82 (0.38) W) compared with the unaffected side (0.58 (0.33) W) ($p = 0.03$) during the progressive hop test at 120 hops.min^{-1}. Peak hip joint moment (N·m·kg^{-1}, mean (SD)) during loading was greater on the unaffected side (1.4 (0.47) N.m) compared with the affected side (1.2 (0.38) N.m) ($p = 0.003$) during the maximal height hop test. There were no significant differences between sides for all other kinetic characteristics (Supplementary file 3).

Correlation with contact time

There was a strong negative correlation (r range: -0.53 to -0.86) between contact time and stiffness (vertical and leg) for all hop tasks, except for the progressive hop test at 96 hops.min^{-1} during which there is a decrease in contact time as vertical stiffness increased (Table 4, Fig. 1). There was a strong negative correlation (r range: -0.54 to -0.74) between contact time and ankle stiffness during self-selected hopping, maximal height hopping, and the progressive hop test at 120 hops.min^{-1} (Table 4). There were moderate negative correlations (r range: -0.44 to -0.49) between contact time and ankle stiffness at 132 hops.min^{-1}, and during the progressive hop test at 108 hops.min^{-1}. There was a moderate negative correlation (r range: -0.32 to -0.37) between contact time and stiffness (vertical, leg and ankle joint) at 96 hops.min^{-1} (Table 4).

Discussion

The main finding of this study was symmetry between sides in the overall limb and ankle joint mechanics, and temporospatial characteristics during single-leg hopping efforts at different cadences in active recreational runners with unilateral AT. There were small inter-side differences observed in hip and knee joint kinematics and kinetics during loading possibly associated with AT, however, the small differences may not be clinically relevant. Contact duration, which can be measured in the clinical setting, was strongly correlated with vertical and leg stiffness, and ankle joint stiffness when single-leg hopping was performed at a self-selected cadence.

The current study contrasts a previous study which observed during runners with unilateral AT had shorter contact duration on the affected side during running [47], suggesting a compensatory strategy to avoid pain or the perceived threat of experiencing pain. Running and hopping are inherently different tasks with horizontal and vertical translation of the COM and an antiphase pattern of movement between limbs during running [32, 48]. It is plausible that these differences which are redundant

during hopping [48], and do not in fact induce the inter-side differences observed during running [47]. Although single-leg hopping provoked pain in the mid-portion of the Achilles tendon, runners with unilateral AT demonstrated symmetrical lower limb mechanics between sides. These findings suggest that in the absence of significant biomechanical asymmetries, continuing to run may not necessarily exacerbate asymmetry-related issues. However, further research is needed before making definitive clinical recommendations.

A previous study did report lower leg stiffness on the affected side during hopping in athletes with AT [49], however, the method used to calculate leg stiffness utilised contact mats to estimate GRF based on contact duration [33]. This approach to calculate leg stiffness is most accurate when the participant hops at a self-selected cadence which can range from 120 to 132 hops·min^{-1} [33], hence, this previous study may have underestimated leg stiffness compared to the values observed in the current study. Importantly, this previous study examined athletes from various sports, whose baseline stiffness characteristics may differ from recreational runners with demonstration of difference in leg stiffness between trained and untrained athletes [34]. The current findings extend the knowledge about how leg stiffness may be sensitive to the instrumentation, task, and the sample population.

The differences in joint angle and joint power at the proximal joints (hip and knee) were small within the range of normal inter-limb variability [34, 50]. Only peak hip joint power was found to be 34% greater on the affected side when hopping at 120 hops.min^{-1}. Given that contact time was consistent between sides, this suggests a higher rate of energy absorption during loading at the hip on the affected side. Although this asymmetry was only observed when hopping at a comfortable cadence at (120 hops.min^{-1}), the magnitude of the difference warrants further investigation into what mechanism may lead to a compensatory strategy at the hip joint. This finding aligns with previous findings of altered hip joint mechanics in people with Achilles tendinopathy, which included greater hip adduction impulse and external rotation moments compared to the unaffected side during running [27]. The greater hip joint power observed in the current study may indicate compensation of a proximal segment and redistribution of mechanical characteristics along the kinetic chain [16].

Vertical and leg stiffness are commonly used to quantify the mechanical characteristics of athletes, reflecting how the lower limb responds to loading during dynamic tasks such as running and hopping [42, 48, 51]. In the current study, the strong correlation between contact duration and stiffness during self-selected hopping suggests that temporospatial measures may offer a practical measure for assessing these mechanical properties in clinical settings. These findings reinforce the recommendation to incorporate tests of physical function capacity during the examination of individuals with AT [28].

Clinical implications

From a clinical perspective, contact duration during self-selected single leg hopping is simple to measure [35] and showed a strong negative association with vertical and leg stiffness in this cohort. While it is not proposed that contact duration is a standalone diagnostic metric, monitoring contact duration over time may provide a practical indicator of changes in lower limb mechanical behaviour alongside patient reported outcomes and task performance. Measuring contact duration as a clinical tool should ensure that the task is standardised by being performed with the same parameters across testing sessions and that other factors such as surface and footwear be standardised in addition to monitoring symptoms. The interpretation of any differences should be made with caution given that the current study had a small sample size and included recreationally active runners.

Limitations and future directions

Participants were recruited as a sample of convenience and this may limit generalisability to runners with different training loads or non-runners who experience AT. The sample population was heterogenous and included young and middle-aged adults and both men and women, which may confound results as there was not sufficient power to analyse the effect of age and sex on the results. This study did not include an age-matched control group because the main aim was to examine inter-limb symmetry. Future research is needed to determine whether hop biomechanics differ between people with and without unilateral AT, and to provide normative datasets for comparison.

Participants in the current study were engaged in running and considered a relatively high functioning. Future research should explore whether the inter-side symmetry is observed in runners with more severe functional limitations. Longitudinal studies which monitor the biomechanical characteristics and inter-limb symmetry have the potential to provide information about how mechanical characteristics may change over time and be correlated to performance or injury risk. This in-depth information could help identify whether the measure of lower limb biomechanical characteristics have clinical relevance and utility in the management of people with AT.

Conclusion

In runners with unilateral AT, lower limb mechanical characteristics during single-leg hopping were symmetrical, with only minor differences observed in hip and knee joint mechanics at specific cadences. These findings suggest no obvious inter-limb compensatory strategy during single leg hopping in habitual runners with unilateral AT. The strong association between contact duration and stiffness supports the pragmatic use of temporospatial metrics as part of a broader clinical assessment, while acknowledging that larger studies are needed to define thresholds and responsiveness.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13102-026-01714-9.

Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

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Authors' contributions
JM led the conceptualisation and design of the study, conducted the primary testing and data analysis, and writing the manuscript. PM, LP, AGar, and AGup contributed to the development of the methodology, assisted with data collection and interpretation, and provided critical revisions to the manuscript. All authors read and approved the final manuscript.

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Data availability
All data relevant to the study are included in the article or are available as supplementary files. Additional raw data may be available by contacting the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The study was approved by the Monash University Human Research Ethics Committee (Project ID: 17888) and all procedures were in accordance with the National Statement on Ethical Conduct in Human Research (2007, updated 2018), and the Declaration of Helsinki regarding human research. All participants were provided with a plain language statement and gave informed consent prior to participation.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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