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SYSTEMATIC REVIEW

Stiffness as a Risk Factor for Achilles Tendon Injury in Running Athletes

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Abstract

Background Overuse injuries are multifactorial resulting from cumulative loading. Therefore, clear differences between normal and at-risk individuals may not be present for individual risk factors. Using a holistic measure that incorporates many of the identified risk factors, focusing on multiple joint movement patterns may give better insight into overuse injuries. Lower body stiffness may provide such a measure.

Objective To identify how risk factors for Achilles tendon injuries influence measures of lower body stiffness.

Methods SPORTDiscus, Web of Science, CINAHL and PubMed were searched for Achilles tendon injury risk factors related to vertical, leg and joint stiffness in running athletes.

Results Increased braking force and low surface stiffness, which were clearly associated with increased risk of Achilles tendon injuries, were also found to be associated with increased lower body stiffness. High arches and increased vertical and propulsive forces were protective for Achilles tendon injuries and were also associated with increased lower body stiffness. Risk factors for Achilles tendon injuries that had unclear associations were also investigated with the evidence trending towards an increase in leg stiffness and a decrease in ankle stiffness being detrimental to Achilles tendon health.

Conclusion Few studies have investigated the link between lower body stiffness and Achilles injury. High stiffness is potentially associated with risk factors for Achilles tendon injuries although some of the evidence is controversial. Prospective injury studies are needed to confirm this relationship. Large amounts of high-intensity or high-speed work or running on soft surfaces such as sand may increase Achilles injury risk. Coaches and clinicians working with athletes with new or reoccurring injuries should consider training practices of the athlete and recommend reducing speed or sand running if loading is deemed to be excessive.

Key Points

High braking forces and running on soft surfaces such as sand have previously shown a clear increase in risk for Achilles tendon injuries and were also associated with higher lower extremity stiffness measures.

Factors shown to be protective for Achilles injury were also associated with higher stiffness measures.

There is a potential link between high lower extremity stiffness measures and risk for Achilles injuries, which warrants further prospective investigation.

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1 Introduction

Chronic Achilles tendon injuries, commonly referred to as tendinopathy or tendonitis (from here on referred to as Achilles injures), are a frustrating injury for athletes owing to their slow recovery time and tendency for reoccurrence. When classified for 'severity' based on the number of days off training and prevalence, Achilles injuries were the most severe lower limb injuries, with only upper back injuries more severe in elite triathletes [1, 2]. In club and development triathletes, Achilles injuries ranked as number one on the severity scale [2].

Three main themes apparent in the literature regarding the mechanism of Achilles injury include tensile loading [3], shearing [4] and hyperthermia [5, 6]. For overuse type tendon injuries, it has been suggested that 'non-homologous loading' leads to localised tendon damage resulting in an area of weakened tissue [7]. This area of weakened tissue gradually becomes larger if loading occurs before healing is complete, resulting in a cycle of progressively weakened and dysfunctional tissue. Ex vivo cyclic loading has shown tendon stiffness decreases over time and hysteresis becomes greater, which is believed to indicate accumulated damage [8]. It is unlikely that the natural motion of running would produce forces that could lead to macroscopic disruption of the tendon structure. It is conceivable, however, that injurious movement patterns lead to microscopic but accumulating damage, which ultimately results in pain and dysfunction for the athlete. Loading through the tendon during cycling is significantly lower compared with running [9–11]. It is therefore more likely for injury to occur during running. The focus for this review was therefore directed at running.

Research into the nature of overuse Achilles tendon injuries is extensive, yet uncertainty remains around how to identify athletes susceptible to Achilles tendon injury. Our recent review on Achilles tendon injury risk factors associated with running identified two variables, high vertical forces and high arch, which showed strong evidence for reduced injury risk. High propulsive forces and running on stiffer surfaces may also be protective [12]. Only one biomechanical variable, high braking force, showed clear evidence for increasing Achilles injury risk. The majority of the biomechanical risk factors examined showed unclear results, which may be attributed to the multifactorial nature of Achilles overuse injuries.

Many risk factors are related to how the athletes' body interacts with the environment during gait including ground reaction forces, muscle activity prior to landing and immediately post-ground contact and joint motion throughout stance. The largely inconclusive results for individual risk factor analysis highlight the need for an alternative method of assessing injury risk [12]. Dynamical systems theory suggests that a movement's end result can be achieved by multiple movement patterns [13–16]. It is possible that an injury endpoint does not arise from a single identifiable factor but from multiple factors working together to cause eventual breakdown of the tissue [15]. Multiple combinations of multiple factors would give the observed results for single-risk factor analysis, small-effect sizes with large confidence intervals. Identifying single measurements that are influenced by many of the known risk factors, may provide a better measure of injury risk. While lower extremity stiffness does not reflect the properties of the tendon, it does reflect how the different tissues and joints work together during the first half of stance phase. Lower extremity stiffness may therefore provide a means of identifying factors causing stress to the tendon tissue during functional movements without having to use more complex localized measures such as tendon stiffness. Total leg stiffness during hopping had a potentially large negative effect size (-1.73 ± 1.71) when comparing Achilles injured and uninjured runners [12]. Single-leg hopping on a sled apparatus resulted in significantly higher vertical stiffness in a cohort of Achilles injured patients compared with healthy volunteers [17]. Stiffness is also modified by many of the Achilles injury risk factors identified [12]. A link between individual risk factor measures and stiffness variables, for example higher leg stiffness associated with higher braking forces and soft surfaces, would indicate a potential for the use of stiffness as a more holistic measure of Achilles injury risk.

Stiffness is a pseudo measure relating to how the lower body interacts with the ground upon landing. The body is modelled as a point mass balanced on a compressible spring while the joints are modelled as torsional springs with each 'spring' having a specific stiffness, *k* (see Fig. 1)

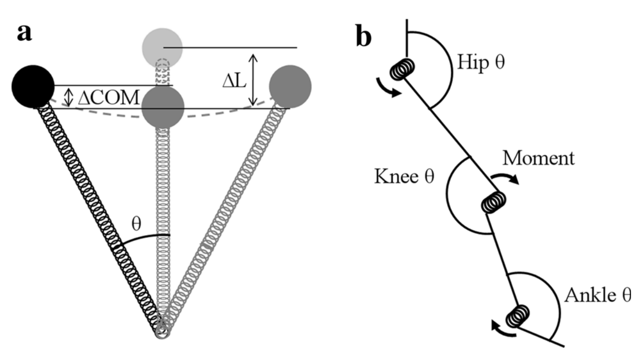

Fig. 1 Biomechanical stiffness models for changes in (**a**) vertical and leg stiffness [19], and (**b**) joint stiffness [18] during running. Vertical stiffness is calculated from maximum vertical force and centre of mass (COM) displacement. Leg stiffness is calculated from maximum vertical force and 'leg spring' compression (*L*). Joint stiffness is calculated from changes in joint angles and moments

[18, 19]. Despite the simplicity of the model, the mechanics of gait are efficiently represented. Centre of mass displacement is achieved via compression of the 'leg spring' whose length is modified via rotation of the joints (Fig. 1a, b). The rate and extent of joint rotation is controlled by the surrounding muscles, ligaments and tendons working against the externally applied force. Control of stiffness is likely to be both centrally mediated from the cortex and possibly central pattern generators as well as through reflex activation [20–22].

Hopping and running tasks are both used for stiffness analysis. The task and biomechanical stiffness model used are largely determined by the constraints of the testing environment and equipment available. The basic equations for estimating stiffness are:

$$k_{\text{vertical}} = \frac{F_{\max}}{\Delta y}, \quad (1)$$

$$k_{\text{leg}} = \frac{F_{\max}}{\Delta L}, \quad (2)$$

$$k_{\text{joint}} = \frac{\Delta M}{\Delta \theta}, \quad (3)$$

where $F_{\max}$ is the maximum vertical force, Δy is the centre of mass displacement, ΔL is the change in 'leg spring' length, ΔM is the change in joint moment and $\Delta \theta$ is the change in joint angle. Owing to the biarticular nature of the gastrocnemius muscle there is potential for both the knee and ankle to play a role in Achilles injuries.

There have been few studies investigating the link between stiffness and Achilles tendon injuries. As Achilles injuries are the result of cumulative damage and are a progressive injury it is likely that a number of risk factors come together in each individual to result in the injury. Each risk factor by itself may be statistically insignificant. The authors believe that joint and leg stiffness provide a holistic view of how the lower limb is functioning during running. Stiffness therefore could provide a measure that was able to pick up risk by taking into account all the different risk factors of the individual athlete. The limitations regarding methods used to quantify stiffness, in particular the complex link between global measurements and local alterations, means that associations with injury may be difficult to determine.

2 Objective

Using the risk factors for Achilles injuries identified in our previous review [12], vertical ground reaction force, braking and propulsive force, surface stiffness and arch height, the objective of this systematic review was to determine whether there is a link between running related risk factors for Achilles tendon injuries and lower extremity stiffness. The findings will direct further research into measures for identifying Achilles tendon injury risk.

3 Methods

Cochrane Collaboration review methodology (literature search; assessment of study quality; data collection of study characteristics; analysis and interpretation of results; recommendations for clinical practice and further research) was used [23].

3.1 Search Parameters and Criteria

Databases PubMed, SPORTDiscus, CINAHL and Web of Science to October 2015 were searched for terms linked with Boolean operators ("AND", "OR", "NOT"): vertical/leg/joint/ankle/knee/hip stiffness; arch height; braking force; vertical force; running distance; running experience; eccentric strength; concentric strength; knee flexion; ankle dorsiflexion; ankle eversion; ankle coupling; tibial rotation; muscle activity; running speed; age; sex. Papers were selected based on title, then abstract and finally text. Relevant references from the text of selected articles were also retrieved and included in the analysis. Papers were excluded if their content included the following topics: any movement that was not running such as vertical drop jump; tendon stiffness; musculoarticular stiffness; oscillation stiffness method; passive stiffness; sled testing; change of direction; stretching; upper body, without including running or hopping stiffness measures. Case reports, reviews, editorials, letters to the editor and all animal studies were excluded. Papers were included that specifically addressed aspects of training or racing encountered by triathletes, such as fatigue and running off the bike.

A total of 13,529 papers were identified of which 5762 were duplicates. After selection for inclusion criteria and elimination based on exclusion criteria, 57 papers were left for inclusion into the final review (Fig. 2).

3.2 Assessment of Study Quality for Systematic Review and Data Extraction

Owing to the diversity of study types (between subject repeated measure, within subject repeated measure and correlation analysis as reported in Electronic Supplementary Material Appendix S1), and the known influences on stiffness, a new nine-item study inclusion criteria scale was developed based on the PEDro [24] and Bizzini scales [25] (Table 1). Exclusion criteria as well as inclusion criteria were deemed important as this gave better insight into the characteristics of the groups being studied as the nature of

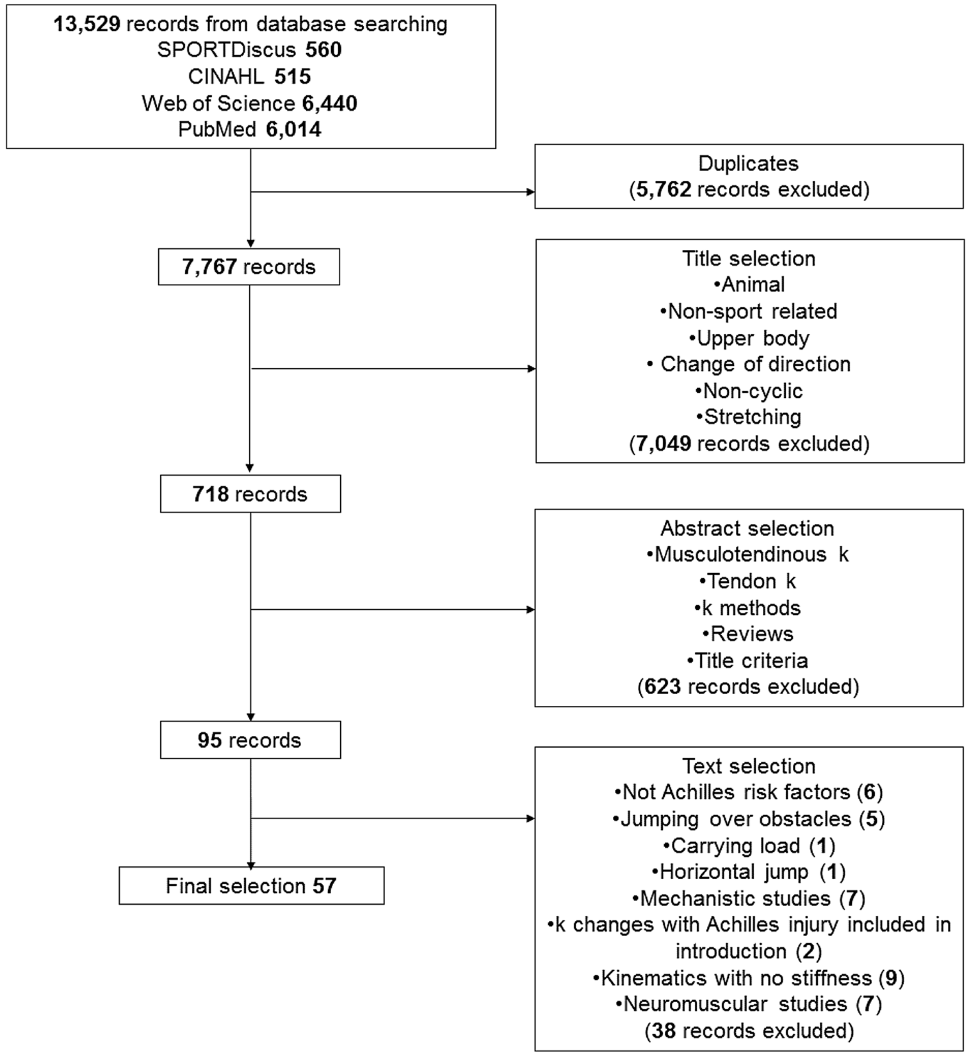

Fig. 2 Flow of information through the different phases of the systematic review. *k* stiffness

Table 1 Study quality score criteria

Number	Criteria
1	Eligibility criteria were specified (specifically activity level)
2	Exclusion criteria described (specifically injury criteria)
3	Each group contained at least ten participants
4	Groups were similar at baseline for height, weight, sex and age (no significant difference) or results were weight adjusted
5	Randomisation was employed where necessary
6	Frequency and/or horizontal velocity were specified
7	A measure of change in stiffness and variability for at least one key variable was given
8	At least five landings per person per condition were used for stiffness analysis
9	Statistical analysis was detailed

the research does not allow blinding and true randomisation. Body weight normalisation of results was important when groups were significantly different owing to the effect that body weight has on stiffness measures. Where randomisation was not possible such as cross-over with only one measurement, or a reason for lack of randomisation was given, the study quality point was awarded. Stiffness changes required two means, effect sizes or correlations and required confidence intervals or standard deviations to meet these criteria. The quality scores based on the paper selection criteria ranged from 4 to 9.

3.3 Analysis and Interpretation of Results

All differences in stiffness between study conditions were converted into effect sizes. Effect sizes with 95 % confidence limits were calculated from means and standard deviations.

Both between- and within-subject repeated-measure effect sizes were calculated as the difference between the means divided by the pooled standard deviation. It is acknowledged that this method may overestimate the effect size and confidence interval in within-subject analysis, owing to the lack of complete independence; however, the lack of exact p values in the majority of studies prevented the use of alternative methods [26].To maintain consistency, all results were treated with the same method regardless of reporting of p values. Correlations were converted to effect sizes by $d = \frac{2r}{\sqrt{1-r^2}}$ (where d = effect size and r = correlation coefficient) with confidence intervals calculated using the Fisher's z transformation prior to effect-size conversion [23]. Study characteristics and quality scores are reported in Electronic Supplementary Material Appendix S1. Stride rate analysis in a variety of running populations ranged from 1.3 to 1.7 Hz [27, 28]; therefore, frequency conditions were limited to the range between 1.5 and 2.5 Hz (preferred hopping frequency = ~2.2 Hz). Stiffness differences related to the factors previously identified as clearly increasing or decreasing risk of Achilles tendon injuries [12], are presented in Table 2 while all other risk factors are presented in Table 3. An effect size of 0.2–0.6 was considered small, 0.6–1.2 moderate, 1.2–2.0 large and greater than 2.0 very large [29].

4 Results

In our previous review on risk factors for Achilles injuries in running athletes, high peak braking force was shown to increase Achilles tendon injury risk, while high peak propulsive and vertical force, increasing surface stiffness and increasing arch height were protective [12]. Two studies investigated braking force and vertical and leg stiffness [30, 31]. Increasing braking force showed a large increase in vertical and leg stiffness when running at preferred pace [30]. However, when running at 95 % of VO_{2max} (maximum volume of oxygen uptake) there was no clear effect [31] (Table 2). Increased propulsive force (F_{ymax}), which demonstrated small protective effects for Achilles injuries [12], was associated with moderate to large increases in both vertical and leg stiffness [30, 31]. Three studies reported the relationship between vertical force (F_{zmax}) and vertical and leg stiffness [30, 32, 33]. Running at preferred pace showed clear increases in vertical and leg stiffness with increasing force [30]. Increased vertical force with sprinting was associated with an unclear increase in vertical and an increase in leg stiffness [33]. Treadmill running at 80 % VO_{2peak} (peak volume of oxygen uptake), however, gave an increase in leg stiffness and decrease in vertical stiffness, both of which had unclear effect sizes [32].

As surface stiffness or arch height was increased, risk of Achilles tendon injury was reduced [12]. Low arches and low surface stiffness may be harmful to tendon health [12]. Three studies investigated changes in vertical stiffness [34–36], six leg stiffness [34–39], and one knee and ankle stiffness with changing surface stiffness [37]. There was an increase in vertical stiffness when running across a surface with increasing stiffness at 3.0 m/s [34]. All other results for vertical stiffness were not clear and showed decreased or unchanged stiffness. Of the seven comparisons that showed clear results, all but one showed decreased leg stiffness with increasing surface stiffness for both hopping and running [34, 37, 39]. All results for knee and ankle stiffness during bipedal hopping were unclear [37]. The trend was for decreasing ankle stiffness and increasing knee stiffness as surface stiffness increased. Increasing the stiffness of the midsole resulted in small decreases in both knee and ankle stiffness [40]. Only one study has compared arch height and leg and joint stiffness [41]. Increasing arch height was associated with an unclear but moderate increase in leg stiffness and a moderate increase in knee stiffness [41].

Other risk factors (pace variables, age, sex, footwear, muscle activity patterns, intensity and rearfoot angle) did not show distinct association with Achilles tendon injury but could still be involved in the injury process [12]. The triathlon-specific variable of transitioning from cycling to running was also considered for injury risk potential. As fatigue cannot be discounted from any cycle to run transition effects, the effects of fatigue was incorporated. Results were variable with only increasing muscle activity and decreasing contact time showing conclusive increased joint stiffness (Table 3). The effect of these risk factors on stiffness are given in Table 3 and the general trend of the data summarised.

Velocity, and parameters associated with velocity, were measured for all stiffness variables. An increase in velocity was generally associated with moderate to large increases in vertical stiffness [30, 33, 42–44]. Leg, knee and ankle stiffness showed trivial to small increases with increasing velocity [30, 33, 42, 43, 45]. Increasing contact time resulted in decreased vertical [30, 33, 46], leg [30, 33, 47–49] and ankle stiffness [45, 50, 51]. Increasing stride rate resulted in increased vertical [30, 32, 33, 43, 52–54], leg [30, 33, 43, 48, 50, 53–56], knee and ankle stiffness [50, 56]. Stride length however was variable, giving increases [30, 33, 43], decreases [31, 33, 49] and no change [30, 43] for both vertical and leg stiffness.

Bipedal hopping at 2.2 and 2.0 Hz resulted in male individuals having moderately larger leg stiffness [57] and moderately smaller leg stiffness [58] compared with female individuals. At 2.5 Hz [58] and preferred hopping frequency [59, 60], the differences were small and both

Table 2 Effect of the five clear Achilles tendon risk factors on lower body stiffness measures. Clear results (CI does not cross zero [29]) are shaded for clarity. A negative effect size indicates that decreasing the variable of interest or the first condition stated resulted in a lower stiffness measure

Factor	Change	Movement	Vertical		Leg		Knee		Ankle		Reference
			ES	95 % CI	ES	95 % CI	ES	95 % CI	ES	95 % CI	
F_{ymin}	Correlation	Run (preferred)	*1.57*	*0.14, 3.70*	1.07	−0.28, 2.90					[30]
	Correlation	Run (95 % VO_{2max})			−0.06	−1.86, 1.70					[31]
F_{ymax}	Correlation	Run (preferred)	*1.79*	*0.30, 4.06*	0.81	−0.52, 2.50					[30]
	Correlation	Run (95 % VO_{2max})			*1.91*	*0.10, 5.00*					[31]
F_{zmax}	Correlation	Sprint (max)	0.87	−0.24, 2.25	*1.42*	*0.24, 3.04*					[33]
	Correlation	TM run (80 % VO_{2peak})	−0.45	−1.75, 0.70	0.95	−0.21, 2.43					[32]
	Correlation	Run (preferred)	*1.85*	*0.35, 4.18*	*2.98*	*1.12, 6.15*					[30]
Surface *k*	21.3–533 kN/m	Run (3.0 m/s)	*2.27*	*0.90, 3.64*	*−2.88*	*−4.48, −1.28*					[34]
	Cont. 21.3–cont. 533 kN/m		0.46	−1.14, 2.07	*−3.58*	*−5.07, −2.09*					
	220–950 kN/m	Run (3.7 m/s)	−0.56	−3.42, 2.29	0.23	−4.15, 4.60					[36]
	450–950 kN/m		−0.37	−2.83, 2.10	0.11	−4.03, 4.25					
	75–950 kN/m		−1.22	−5.05, 2.61	0.78	−3.31, 4.87					
	Low–high	Run (5.0 m/s)	0.04	−6.99, 7.07	−1.14	−5.40, 3.12					[35]
	30–35,000 kN/m	Bi hop (2.2 Hz)			*−12.86*	*−13.86, −11.87*	3.09	−117.07, 123.24	−3.62	−47.56, 40.31	[37]
	60.9–35,000 kN/m				*−7.95*	*−10.33, −5.57*	0.07	−95.41, 95.55	−0.06	−36.77, 36.65	
	30–60.9 kN/m				*2.47*	*0.02, 4.93*	2.69	−132.42, 137.80	−3.05	−54.54, 48.45	
	26.1–50.1 kN/m	Bi hop (2.0 Hz)			−2.29	−19.84, 15.27					[38]
	27–411 kN/m (expected)	Bi hop (2.2 Hz)			*−5.15*	*−6.88, −3.42*					[39]
	27–411 kN/m (surprise)				*−6.00*	*−7.63, −4.38*					
	Cont. 27–cont. 411 kN/m				*−8.57*	*−10.14, −7.01*					
Arch height	Low arch–high arch	Run (3.4 m/s)			0.65	−0.07, 1.38	*0.63*	*0.61, 0.65*			[41]

All clear effects (CIs do not cross zero) are italics

bi hop bipedal hopping, *CI* 95 % confidence interval, *cont.* continuous stiffness surface, *ES* effect size, F_{-ymax} maximum propulsive force, F_{ymin} maximum braking force, F_{zmax} maximum vertical force, *max* maximum effort, *TM* treadmill, VO_{2max} maximum oxygen uptake, VO_{2peak} peak oxygen uptake

Table 3 Effect of Achilles tendon injury risk factors on lower body stiffness measures. Clear results (CI does not cross zero [29]) are shaded for clarity. A negative effect size indicates that decreasing the variable of interest or the first condition stated resulted in a lower stiffness measure

Factor	Change	Movement	Vertical		Leg		Knee		Ankle		Reference
			ES	95 % CI	ES	95 % CI	ES	95 % CI	ES	95 % CI	
Velocity	Correlation	Sprint (max)	0.80	−0.31, 2.15	0.63	−0.47, 1.92					[33]
	Correlation	Sprint (max)	1.84	−0.11, 5.29	0.18	−1.74, 2.25					[43]
	Correlation 100 m	Sprint	1.28	−0.55, 4.17							[44]
	70 % (7.0 m/s) –80 % (7.8 m/s)	Sprint			0.91	−33.66, 35.49	−0.10	−4.37, 4.17	0.00	−1.49, 1.49	[45]
	80–90 % (8.8 m/s)				0.59	−53.21, 54.39	0.33	−4.76, 5.42	0.00	−1.74, 1.74	
	90–100 % (9.7 m/s)				0.04	−58.39, 58.46	0.51	−10.96, 11.99	0.20	−1.91, 2.31	
	70–100 %				1.58	−39.83, 42.99	0.64	−10.48, 11.77	0.22	−1.69, 2.13	
	Correlation	Run (preferred)	*1.73*	*0.26, 3.97*	0.15	−1.23, 1.58					[30]
	2.5–3.5 m/s	Run	0.71	−7.32, 8.74	−0.15	−3.33, 3.02	0.76	−1.85, 3.37	0.50	−2.52, 3.53	[42]
	3.5–4.5 m/s		1.41	−10.30, 13.12	0.75	−2.24, 3.74	0.85	−2.76, 4.45	0.62	−2.94, 4.17	
	4.5–5.5 m/s		0.80	−10.66, 12.25	0.00	−2.08, 2.08	0.23	−3.55, 4.00	−0.02	−3.68, 3.65	
	3.0–4.0 m/s	TM run			0.10	−2.57, 2.77					[122]
Contact time	Correlation	Sprint (max)	−0.80	−2.15, 0.31	−1.06	−2.52, 0.07					[33]
	Correlation	Run (preferred)	*−1.79*	*−4.06, −0.30*	*−1.70*	*−3.92, −0.24*					[30]
	Correlation	Run (vVO_{2max})			*−6.60*	*−20.87, −1.72*					[49]
	Short-preferred	Run (3.3 m/s)			−2.49	−5.37, 0.39					[48]
	Preferred-long				*−3.44*	*−5.72, −1.17*					
	Short-preferred	Bi hop (preferred)			−1.14	−9.73, 7.44					[47]
	Eld. correlation	Bi hop							*−1.54*	*−2.80, −0.57*	[51]
	70 % max correlation	Sprint							*−2.76*	*−6.32, −0.79*	
	100 % max correlation								*−4.69*	*−10.18, −1.91*	
SR/Hz	Correlation	Sprint (max)	*2.08*	*0.74, 4.03*	0.90	−0.22, 2.29					[33]
	Correlation	Sprint (max)	1.67	−0.23, 4.94	0.29	−1.60, 2.42					[43]
	Correlation	TM run (80 % VO_{2peak})	*3.23*	*1.49, 6.02*							[32]
	Correlation	Run (preferred)	*2.01*	*0.47, 4.44*	0.24	−1.11, 1.71					[30]
	−8 %—preferred	Run (78 % VO_{2max})	0.95	−2.22, 4.12	*0.55*	*0.46, 0.64*					[75]
	Preferred—+8 %		1.28	−2.06, 4.61	*2.43*	*2.38, 2.48*					
	−26 %—preferred	TM run (2.5 m/s)	*8.85*	*5.62, 12.09*	*3.09*	*0.10, 6.07*					[53]
	Preferred—+30 %		5.69	−0.78, 12.16	2.53	−0.70, 5.76					
	−30 %—preferred	Run (3.3 m/s)			0.44	−2.30, 3.18					[48]
	Preferred—+30 %				1.43	−4.99, 7.86					
	1.5–2.1 Hz	Bi hop			*0.72*	*0.48, 0.96*	*0.52*	*0.28, 0.76*	*0.65*	*0.52, 0.77*	[50]

Table 3 continued

Factor	Change	Movement	Vertical		Leg		Knee		Ankle		Reference
			ES	95 % CI	ES	95 % CI	ES	95 % CI	ES	95 % CI	
	1.5–2.1 Hz (/kg)	Bi hop			*1.13*	*1.00, 1.26*	0.55	−10.23, 11.33	0.80	−2.48, 4.09	[56]
	1.5–2.2 Hz (D)	Uni hop			*2.43*	*2.38, 2.48*					[55]
	1.5–2.2 Hz (ND)				*1.75*	*1.71, 1.79*					
	−20 %—preferred	Uni hop	0.90	−5.48, 7.28							[52]
	Preferred—+20 %		1.23	−5.45, 7.90							
Stride length	Correlation	Sprint (max)	−0.61	−1.89, 0.49	−0.56	−1.83, 0.54					[33]
	Correlation	Sprint (max)	0.59	−1.24, 2.90	0.00	−1.99, 1.98					[43]
	Correlation	Run (95 % VO_{2max})	−0.39	−2.33, 1.29							[31]
	Correlation	Run (preferred)	0.75	−0.58, 2.41	−0.07	−1.49, 1.31					[30]
	Correlation	Run (vVO_{2max})			*−4.06*	*−13.23, −0.66*					[49]
Age	Men–boys	Bi hop (1.5 Hz)			−0.79	−7.03, 5.45					[61]
	Young–eld. (50 % max)	Bi hop					0.19	−2.38, 2.75	0.34	−0.95, 1.62	[51]
	Young–eld. (75 % max)						0.64	−3.60, 4.87	0.00	−1.53, 1.53	
	Young–eld. (100 % max)						−0.06	−4.24, 4.11	*−1.51*	*−2.96, −0.06*	
	16–20–36–60*y*	Run (3.3 m/s)					0.00	−0.10, 0.10	*−0.47*	*−0.69, −0.24*	[40]
	<35–50 + *y*	Run (3.8–4.1 m/s)	0.74	−13.63, 15.11			*−0.50*	*−0.97, −0.03*	*0.71*	*−0.37, 1.78*	[63]
	Young–eld.	Bi hop (2.2 Hz)			−0.01	−0.10, 0.07					[62]
Sex	Female– male	Bi hop (2.0 Hz)			*−0.72*	*−0.79, −0.65*					[58]
	Female–male	Bi hop (2.2 Hz)			*0.68*	*0.57, 0.79*					[57]
	Female–male	Bi hop (2.5 Hz)			*−0.15*	*−0.28, −0.02*					[58]
	Female–male	Bi hop (preferred)			*0.23*	*0.10, 0.36*					[102]
	Female–male	Bi hop (preferred)			−0.06	−0.23, 0.11					[60]
	Female–male	Bi hop (preferred)			*0.36*	*0.27, 0.44*					[59]
	Female 35 + *y*–male 35 + *y*	Run (3.3 m/s)					1.70	1.55, 1.84	0.19	−0.08, 0.46	[40]
Footwear	Barefoot–350-g shoe	TM run (3.6 m/s)	−0.69	−4.06, 2.68	−0.68	−2.13, 0.77					[64]
	Shoe-racing flat (female)	Run	0.22	−30.39, 30.82							[68]
	Shoe-racing flat (male)		0.90	−45.45, 47.25							
	Barefoot–shoe	Hop (2.2 Hz)			*4.00*	*3.30, 4.69*					[66]
	Barefoot–shoe (0-mm midsole)	Run (3.3 m/s)			*−0.08*	*−3.06, 2.90*	0.26	−17.6, 18.12	1.07	−31.8, 33.95	[67]
	0 mm mid–16-mm midsole	Run (3.3 m/s)			*−0.23*	*−2.98, 2.52*	−0.46	−19.2, 18.28	0.07	−35.74, 35.87	[67]
	Soft–hard midsole	Run (3.3 m/s)					*−0.26*	*−0.32, −0.20*	*−0.48*	*−0.62, −0.34*	[40]
	Minimal–standard shoe	TMRun (65 % VO_{2max})	−0.56	−2.85, 1.72	*−0.53*	*−1.99, 0.94*					[65]

Table 3 continued

Factor	Change	Movement	Vertical		Leg		Knee		Ankle		Reference
			ES	95 % CI	ES	95 % CI	ES	95 % CI	ES	95 % CI	
Training status	Untrained–endurance	Bi hop			*1.64*	*1.52, 1.75*	*1.63*	*−5.66, 8.92*	*−4.06*	*−5.90, −2.22*	[71]
RFA	Run correlation	Run (3.4–4.2 m/s)			*−1.06*	*−1.98, −0.29*					[123]
	Static correlation				*−0.93*	*−1.81, −0.17*					
	Closed–opened				*−1.13*	*−3.00, 0.74*					
Intensity	3–4 BW	Bi hop			*0.08*	*−8.43, 8.60*	*1.96*	*−2.46, 6.38*	*1.00*	*−0.63, 2.63*	[69]
	3–6 BW				*0.87*	*−6.57, 8.32*	*7.07*	*3.42, 10.71*	*2.33*	*1.11, 3.56*	
Strength	Pre–post-weighted sled train	Run (3.3 m/s)	0.42	−24.67, 25.51							[72]
Muscle activity	G preact. correlation	Run (preferred)			0.67	−0.98, 2.76			1.15	−0.51, 3.58	[70]
	VL onset correlation	Run (3.4 m/s)			−0.65	−1.77, 0.31					[41]
	Sol preact. correlation	Bi hop			0.90	0.19, 1.71			1.06	0.34, 1.92	[69]
	Lat. G preact. correlation				1.09	0.37, 1.95			0.70	0.00, 1.48	
	Med. G preact. correlation						1.06	0.34, 1.92			
	Eld. sol (BR/PR) correlation.	Bi hop							1.67	0.67, 2.97	[51]
	Eld. med.G(BR/PR) correlation						2.14	1.04, 3.62			
	Eld. lat. G (BR/PR) correlation								2.41	1.26, 4.02	
	Eld. TA (BR/PR) correlation								−1.71	−3.03, −0.71	
	Eld. TA/sol coact. correlation								−1.09	−2.20, −0.19	
Transition	CR–5 % T2	Run (LT)	0.37	−3.58, 4.32	0.59	−1.28, 2.46					[88]
	CR–20 % T2		0.20	−3.68, 4.07	0.35	−1.45, 2.15					
	CR–100 % T2		0.08	−3.63, 3.78	0.20	−1.58, 1.98					
Fatigue	2nd–12th sprint	Sprint (max)	−4.69	−7.40, -1.98	−1.73	−2.25, −1.20					[33]
	25–375 m	Sprint (max)	−3.26	−15.53, 9.01	−1.88	−5.68, 1.92					[43]
	Sprint 1–sprint 2	Sprint	−0.71	−9.61, 8.18	−0.28	−5.71, 5.15					[73]
	Sprint 1–sprint 4		−0.39	−8.06, 7.29	1.13	−3.18, 5.44					
	1st–2nd 100 m	Sprint	−1.11	−14.43, 12.21	−0.62	−5.20, 3.96					[44]
	1st–4th 100 m		−1.43	−17.19, 14.34	−0.24	−6.08, 5.59					
	10–100 %	Run (VO_{2max})	−0.02	−5.10, 5.06	−0.42	−3.21, 2.37					[83]
	10–100 %	Run (95 % VO_{2max})	0.09	−2.51, 0.79	−0.86	−2.51, 0.79					[31]
	Pre–post	TM run (80 % VO_{2peak})	−0.27	−2.62, 2.09	−0.26	−1.16, 0.64					[32]
	Pre–post	Run (78 % VO_{2max})	−0.17	−4.13, 3.79	−0.10	−1.61, 1.41					[75]

Table 3 continued

Factor	Change	Movement	Vertical		Leg		Knee		Ankle		Reference
			ES	95 % CI	ES	95 % CI	ES	95 % CI	ES	95 % CI	
	Pre–post	Run (70 % VO_{2max})	1.30	0.94, 1.66	0.42	−0.01, 0.85					[76]
	Pre–post + 7-min max		2.82	2.54, 3.11	0.28	-0.03, 0.59					
Fatigue	0–2 h	TM run (2.8 m/s)	0.01	−5.60, 5.63	0.03	−3.69, 3.75					[78]
	0–4 h		0.31	−5.01, 5.63	0.20	−3.31, 3.72					
	Pre–post-50 min	TM run (65 % VO_{2max})	0.10	−2.62, 2.42	−0.53	−1.99, 0.94					[65]
	Pre–post-exhaustion	Run (VO_{2max})	−0.35	−25.77, 25.08	−0.89	−2.72, 0.95					[49]
	Pre–post-exhaustion	Run (95 % VO_{2max})	0.13	−10.27, 10.53	−0.51	−2.38, 1.36					[84]
	Pre–post-Mt marathon	Run (3.5–3.7 m/s)	−0.67	−5.28, 3.94	−0.57	−1.83, 0.70					[85]
	Pre–post uphill marathon	Run (2.9–2.7 m/s)	−3.90	−6.20, −1.59	−3.68	−4.55, −2.82					[86]
	Pre–post-mountain ultra	Run (3.3 m/s)	0.47	−2.33, 3.25	−0.14	−1.09, 0.82					[80]
	Pre–post-multi-stage race	Run (3.9 m/s)	0.43	−5.07, 5.93							[81]
	Pre–post-cycle sprints	Run (2.8 m/s)	0.08	−3.39, 3.55	0.00	−3.19, 3.19					
	Pre-post	TM run (3.3 m/s)	0.77	−5.16, 6.70	0.83	−0.60, 2.26					[74]
	Pre–3 h post	Run (3.3 m/s)	0.52	−1.49, 2.54	−0.33	−1.24, 0.57					[77]
	Pre–post	Run (3.6 m/s)	0.01	−6.48, 6.50	0.01	−2.84, 2.86					[87]
	1st–4th lap	Run (race)	−0.70	−2.12, 0.72	−0.34	−1.33, 0.65					[82]
	1st lap–finish chute		−0.09	−1.71, 1.54	−0.12	−1.19, 0.95					
	200–1000 m	Run (preferred)	0.31	−0.11, 0.73	*0.52*	*0.11, 0.93*					[30]
	200–2000 m		*−1.73*	*−2.11, −1.35*	−0.03	−0.42, 0.35					
	200–5000 m		*−1.36*	*−2.08, −0.65*	−0.06	−0.49, 0.37					
	Pre-post squats (male)	Bi hop (preferred)	*0.24*	*0.08, 0.40*	0.18	−17.43, 17.78					[60]
	Pre-post squats (female)		0.16	−6.78, 6.97	0.18	−11.28, 11.65					

All clear effects (CIs do not cross zero) are italic

bi hop bipedal hopping, *BR* braking, *BW* body weight, *CI* 95 % confidence interval, *coact.* Coactivation, *CR* control run, *D* dominant kicking leg, *Eld.* Elderly, *ES* effect size, *lat. G.* lateral gastrocnemius, *LT* lactate threshold, *med. G.* medial gastrocnemius, *max* maximum effort, *ND* non-dominant kicking leg, *post* post-running exercise, *PR* propulsive, *preact.* Preactivation, *pref.* preferred, *pre* prior to running exercise, *RFA* rear-to-forefoot angle, *sol* soleus, *SR* stride rate, *T2* transition run, *TA* tibialis anterior, *TM* treadmill, *uni hop* unipedal hopping, *VL* vastus lateralis, vVO_{2max} velocity at VO_{2max}, VO_{2max} maximum oxygen uptake, VO_{2peak} peak oxygen uptake positive and negative. For overground running, men over 35 years of age showed higher knee stiffness but similar ankle stiffness to women over the age of 35 years [40]. Men had greater leg stiffness than boys [61]. Compared with young adults, active older individuals had greater knee and ankle stiffness, except when hopping at 100 % of maximum hopping height [51]. Leg stiffness exhibited no change [62]. Age above 35 years may result in increased vertical stiffness when running [63], a decrease [63] or no change [40] in knee stiffness and either an increase [63] or decrease [40] in ankle stiffness. Wearing shoes caused decreased vertical and leg stiffness compared with running barefoot [64]. Minimalist shoes gave similar results to barefoot running when compared with standard shoes [65]. When hopping, wearing shoes caused an increase in vertical and leg stiffness [66]. However, when comparing barefoot running and shoes with a 0-mm pitch leg stiffness was unchanged while knee and ankle stiffness showed a small and moderate increase, respectively [67]. Racing flats caused vertical stiffness to increase slightly compared with standard shoes [68]. Increased triceps surae activity was associated with increased leg, knee and ankle stiffness [51, 69, 70]. Tibialis anterior activity was positively correlated to decreased ankle stiffness [51]. Endurance training gave greater leg and knee stiffness but reduced ankle stiffness compared with untrained individuals [71]. Increasing hopping intensity based on body weight resulted in small to moderate increases in leg stiffness but larger increases in knee and ankle stiffness [69]. No direct relationship between concentric strength and stiffness have been reported however, a resistance training program that reported an average of 20 % improvement in one repetition maximum for half squat, showed a small increase in vertical stiffness with very large confidence intervals [72].

Fatigue was induced by a large variety of methods and was associated with approximately equal numbers of increased [30, 31, 44, 73–81], decreased [30–33, 43, 44, 49, 65, 73, 82–86] and unchanged [30, 31, 49, 60, 65, 75–80, 82–84, 87] stiffness for both vertical and leg stiffness. Transitioning from cycling to running resulted in small increases in vertical and leg stiffness compared with running alone [88].

Figure 3 provides a summary of the links between risk factors for Achilles tendon injuries and measures of lower leg stiffness.

5 Discussion

Summarising the variables that alter stiffness is a difficult task because of the multifactorial nature of the measurement. Both hopping and running have been used to determine the effect of different variables on stiffness measures. While hopping is a cyclic motion with similar vertical centre of mass motion, the addition of horizontal force and motion adds additional information to the 'spring-mass model'. Hopping is often used as a surrogate for running; however, whether it is a valid surrogate when investigating stiffness is unknown. Small sample sizes and large confidence intervals resulted in effect sizes spanning a wide range of interpretations. Combining effect sizes was difficult owing to each study using different parameters of change to the variable of interest.

5.1 Link Between Stiffness and Clear Achilles Injury Risk Factors

In our previous review on risk factors for Achilles injuries, high braking force was shown to have a clear detrimental effect on Achilles tendon health [12]. Increasing surface stiffness, arch height and propulsive and vertical forces were protective [12]. Running on soft surfaces and having a low arch were therefore interpreted as harmful to the Achilles tendon.

High braking forces were clearly associated with high vertical stiffness. Leg stiffness was also increased with increasing braking force at preferred running pace. A low surface stiffness caused increased leg and ankle stiffness compared with surfaces of higher stiffness. The greater the change in surface stiffness the more distinct the change in stiffness. Large confidence intervals for the joints meant the effect was unclear. It is possible that while the ankle stiffness is increased the knee stiffness is decreased in response to low surface stiffness. Low arch height was clearly related to decreased knee stiffness and showed a negative association with leg stiffness. Therefore, an increase in lower body stiffness associated with high braking forces or low surface stiffness could be related to Achilles tendon injuries. However, an increase in knee and leg stiffness when associated with high arches is potentially protective against Achilles tendon injuries. Increased propulsive force and increased vertical force were also protective for Achilles tendons, yet these were also associated with increases in vertical and leg stiffness. Further prospective research is needed to verify a link between increased stiffness and risk of Achilles injury.

The mechanical properties of the Achilles tendon contribute to only a part of the lower limb stiffness that includes the musculo-articular stiffness of the hip, knee and ankle joints. Runners may exhibit significant variations in lower limb stiffness because of alterations at the patella tendon or fatigue in knee extensor muscles with unknown consequences for the risk of Achilles tendon injury. Joint stiffness does not reflect the intrinsic mechanical properties of the Achilles tendon as it is affected by a wide range of factors: neuromuscular coordination, mechanical properties

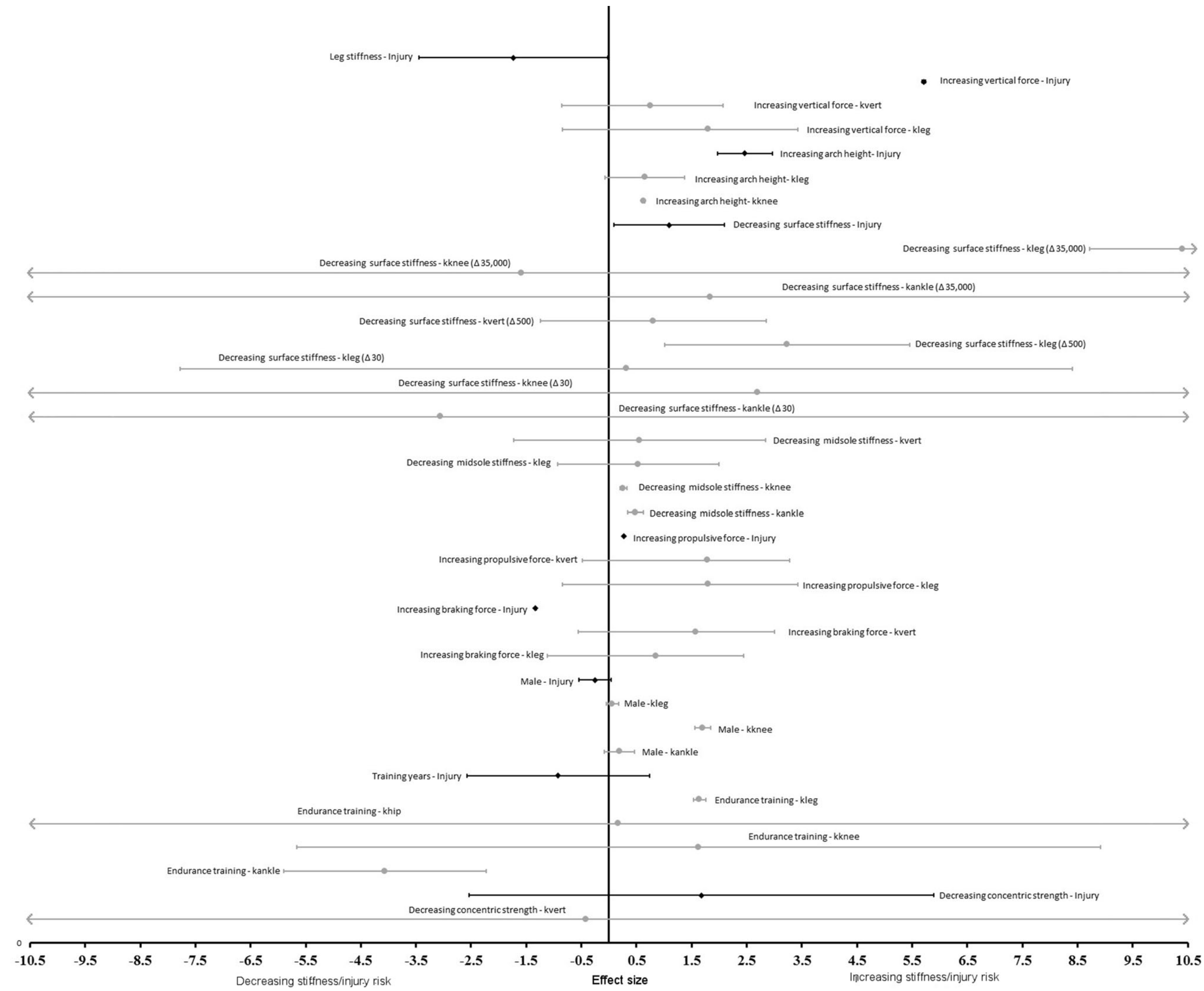

Fig. 3 Forest plot summary of evidence for the association between Achilles injury and lower extremity stiffness variables. *Black diamonds* show the effect size and confidence intervals for the variable of interest with respect to Achilles injury risk. *Grey dots* represent the effect size and associated confidence intervals for the variable of interest with respect to the effect on stiffness. *k* stiffness, Δ change, *vert* vertical

of muscular and non-muscular structures (skin, ligaments, aponeuroses, tendon; [89, 90]). Validated procedures exist to assess the mechanical properties of the tendon (see Seynnes et al. [91] for a review); therefore, prospective studies could be conducted to evaluate the impact of Achilles tendon stiffness on the risk of Achilles tendon injury.

5.2 Link Between Other Achilles Injury Risk Factors and Stiffness

Both protective and injurious factors appear in general to cause increases in stiffness variables. However, many other risk factors have been identified to be potentially related to Achilles injury risk [12]. Overuse injuries are characterised by slow progressive onset, suggesting that the injury is the result of accumulation of damage from low levels of overload. Therefore, the changes to movement patterns would be expected to be small. Combined with the high variability resulting from looking at individual aspects of a movement (e.g., eversion angle in foot pronation), it is probable that risk factors will give inconclusive results when using a single-risk factor analysis approach. Therefore, the effect of other Achilles injury risk factors on lower body stiffness variables was also considered.

5.2.1 Velocity or Running Pace

Pace is a commonly cited risk factor [92] for overuse injuries in general. Faster running pace, or increasing pace too rapidly, are both thought to be associated with injury [46, 92–94]. Vertical stiffness showed an increase in stiffness with increasing velocity; however, the majority of results were unclear. Decreased contact time and increased stride rate (which are inherently related to velocity) caused varying magnitudes of vertical stiffness increase. Increasing stride length was associated with both increases and decreases in vertical stiffness suggesting little to no effect of stride length on vertical stiffness.

Leg and joint stiffness were much less conclusive. The number of small to moderate increases in leg stiffness and no change in leg stiffness with increasing velocity were approximately equal. Variations in the methods used to estimate changes in the length of the 'leg spring' were most likely responsible for this variation in outcomes. Arampatzis et al. [42] investigated changing overground running velocity using the original McMahon and Cheng model (Fig. 1a) [19] and found no change with increasing velocity. However when change in leg length was measured from centre of pressure to centre of mass, rather than estimated, then leg stiffness increased with velocity [42]. Decreasing contact time and increasing stride rate were associated with small to very large increase in leg stiffness, while increasing stride length tended to have little impact on leg stiffness. In the McMahon and Cheng model (Fig. 1; Eqs. 1 and 2), the difference between vertical and leg stiffness resulted from the addition of horizontal motion. Center of mass trajectory is unlikely to follow a perfect curve; therefore, direct measurement is more likely to detect changes in leg length and therefore leg stiffness than the estimated model. Direct measurement may also be more effective at detecting changes in leg length that are the result of overstriding. Factors that modify stride length, such as flight time and angle of attack, occur prior to contact. However, the distance from the centre of pressure to the centre of mass can affect the trajectory of the centre of mass. Therefore, how changes in stride length alter stiffness is dependent on whether the changes in stride length occur during flight or initial stance and the method of measuring stiffness. This could account for the variability in results shown. Contact time, however, is dependent on changes in gait control occurring following ground contact and therefore showed clearer associations with stiffness.

Joint stiffness changes have only been investigated in two studies [42, 45]. Increases in running speed were associated with small to moderate increases in ankle stiffness. Confidence intervals were very large for these measures. At the fastest running speeds (4.5–5.5 m/s) and during sprinting, ankle stiffness appeared not to change. Knee stiffness also showed smaller effect sizes for these velocity changes. Contact time and contact rate showed the same trends as vertical and leg stiffness, increasing stiffness with changes related to increased velocity.

Only one of the effect sizes for increasing velocity was clear, yet the changes to stiffness with stride rate and contact time tended to be more conclusive. Stride length increases with speed while contact time decreases. However, the exact relationship between speed and stride length or contact time is a function of leg length [95]. Therefore, different individuals will adjust running speed through different combinations of altered contact time and stride length. Such individuality in response would account for the greater outcome variability seen when changing velocity compared with altering contact time or stride rate. Different combinations of increased stride rate with decreased contact time, increased stride length, increased propulsive force and increased flight time can all be used to produce the same end running speed.

5.2.2 *Exercise Intensity*

Velocity and intensity are closely associated, with increasing effort and force production required to run at greater pace. Intensity was modified based on force produced normalised to body weight during hopping with a greater target force associated with increased intensity. Ankle, knee and leg stiffness were increased with increased intensity, with greater increases in intensity resulting in larger increases in stiffness. Loading of the Achilles tendon during the braking phase of stance is eccentric with the lengthening of the tendon controlled by action of the triceps surae muscle complex. During the propulsive phase, loading is concentric in nature. Increasing the intensity of the cyclic movement requires greater propulsive muscle force, which is protective against Achilles injury. However, greater loading during landing/braking can be injurious to the Achilles tendon. Muscles and tendons work together to dissipate energy during landing [96]. Tendons protect the muscle during landing by allowing slower eccentric actions. However, for the tendon to lengthen under load, simultaneous contraction of the muscle is required [96].

5.2.3 *Muscle Activity*

The results clearly showed an increase in knee and ankle stiffness with increasing triceps surae muscle activity and overall leg stiffness. Greater braking/propulsive activity ratio resulted in increased stiffness for all three triceps surae muscles. Increasing muscle force increases the stretch of the tendon [96]; therefore, a higher braking activity and associated increased stiffness may cause excessive tendon stretch. Achilles injury risk was associated more with timing of muscle activation between the three muscles of the triceps surae rather than the level of activity [97–100]. Fascicles of the Achilles tendon are supplied by all three muscles, soleus and medial and lateral gastrocnemius. Therefore, uneven activation could lead to fascicles stretching at different rates and to different lengths causing shear forces and consequent microscopic ruptures within the tendon. Gastrocnemius braking/propulsive ratio had a greater effect on stiffness than the soleus, which may also influence the distribution of the load within the tendon. Increased tibialis anterior activity decreased stiffness as did greater tibialis anterior/soleus activity. Increasing tibialis anterior activity may therefore reduce the rate of eccentric loading, protecting the Achilles tendon without sacrificing the triceps surae muscles.

5.2.4 Sex

Male individuals are reported to be more at risk of Achilles injury than female individuals when over the age of 35 years [101]. The effect of sex on stiffness has only been assessed in hopping studies. Both higher and lower stiffness was observed in males when frequency was controlled [57, 58]; however, there were only trivial to small differences between the sexes when allowed to adopt an individual hopping frequency [59, 60, 102]. It is possible that during running there would be little difference between sexes, when running at their preferred stride rate. Increasing age was associated with small or trivial increases in leg and joint stiffness but was dependent on the method of measuring stiffness. At 75 % of maximal hopping height, ankle stiffness was similar but young people had lower knee stiffness. At maximal hopping height, however, knee stiffness was similar while ankle stiffness was lower in the older individuals. This effect is probably owing to differences in muscle strength and tendon mechanical properties which may decrease with age [103] and compensatory movement patterns developed by active older individuals.

5.2.5 Footwear

Footwear is an environmental constraint to the gait task similar to surface stiffness, where a surface of varying stiffness is attached to the foot. The addition of shoes, or changing from racing flats (low cushioning) to standard shoes (high cushioning), however, caused decreased vertical and leg stiffness during running. This effect is opposite to changes in surface stiffness; however, it must be noted that the effect sizes were small and confidence intervals large. The opposite effect can be inferred from a comparison of barefoot running and shod running, which found reduced vertical ground reaction forces when barefoot [104]. It was observed that runners adopted a midfoot strike pattern when runners were barefoot, which resulted in greater ankle stiffness but allowed reduced impact loading [104]. The foot strike pattern rather than the shoe characteristics may be more important in modifying stiffness.

5.2.6 Training Distance

Training distance is another common overuse injury risk factor, but its role in Achilles tendon injuries was unclear [12]. Training distance effect on stiffness has not been measured, but leg and knee stiffness are greater in endurance-trained athletes compared with untrained individuals. Ankle stiffness was notably reduced for the athlete group. However, this is a poor surrogate for training distance as many other differences are apparent between untrained and trained individuals including motivation (training through pain), gait movement skill, muscle strength and tendon loading, which all could influence tendon health.

5.2.7 Pronation

Pronation may or may not be associated with Achilles tendon injuries with the results varying depending on what part of the movement was investigated [12]. The rate of pronation and coupling with tibial rotation may be associated with injury but the evidence is limited [12]. Pronation, measured as rear to forefoot angle was shown to be associated with stiffness during running for both static and dynamic measurements. Increasing the angle (pronation) resulted in decreased leg stiffness. Reducing normal pronation increases impact loading [105]; therefore, increased pronation is likely a protective adaptation. Proprioceptive feedback is important in tuning muscle control and movement patterns to achieve the desired task [106]. Therefore, the level of pronation is likely an adaptation associated with muscle strength and forces unique to the task and individual rather than a direct causative factor for injury.

5.2.8 Triathlon-Specific Risk Factors

In triathlon, not only are the purely running related risk factors important, but also factors associated with combining three disciplines in the one race or training session. Transitioning from cycling to running can result in feelings of reduced coordination and heavy legs [107]. This period of transition between the two disciplines is believed to increase injury risk. Running economy [107–110] is reduced in triathletes following cycling compared with isolated running. Kinematic changes have been reported following cycling [108, 111]. Others have reported no changes in kinematics but altered muscle activity in some athletes [112–114]. Proprioceptive feedback adaptations for postural control persist for a short period following cessation of running or cycling activity in triathletes [115]. Loss of proprioceptive feedback has been shown to affect interjoint coordination [116]. However, the effect of fatigue cannot be isolated from coordination effects when assessing gait changes following cycling.

Fatigue was induced in a variety of ways. Repeated sprints tended to cause reduced vertical and leg stiffness [33, 44, 73], while sustained running at more aerobic intensities (i.e., <75 % VO_{2max}) caused increased stiffness depending on the intensity and the time [76–78, 87]. There may be no effect of fatigue on lower body stiffness or changes may be race distance specific. Shorter distance athletes may experience decreased leg stiffness as fatigue from high-intensity running develops. Longer distance athletes may experience increases in stiffness as a race or training session progresses. Fatigue induced by cycling sprints had no effect on stiffness [79].

The effect of transitioning from cycling to running has only been directly measured in one study [88]. Vertical and leg stiffness showed small, unclear increases in leg and vertical stiffness when running at lactate threshold. Changes in stiffness were largest immediately following cycling and decreased as the run progressed. During an International Triathlon Union Championship race, stiffness decreased throughout the run but athletes were able to increase stiffness for the sprint down the finish chute. The use of continuous drafting compared with alternative drafting and non-drafting resulted in reduced stride length and increased stride rate. Drafting reduces the energy cost of cycling [117]. Therefore, gait changes following cycling are more likely the result of muscular fatigue than coordination changes.

In risk-factor analysis, looking at how individual risk factors impact stiffness may not give the whole picture. Related variables may have very different effects on stiffness, as could be seen with velocity, stride rate and stride length. Humans have high levels of variability in their movement as a result of variable anthropometry, training, skill and learning processes and therefore changes to movement patterns in response to changing task constraints are likely to be variable as well. Low stiffness has been suggested to be associated with increased risk of soft-tissue injuries [118]. However, this analysis suggested there is potential for increased stiffness to be detrimental to tendon health. Whether high stiffness can be used to predict Achilles tendon injuries during running needs to be investigated further in prospective studies.

Coaches and clinicians should be aware that increased lower body stiffness during running may be associated with Achilles tendon injury risk. Athletes returning from injury should be advised to limit activities that result in increased stiffness. Activities associated with increased stiffness include high-intensity/speed running and running on soft surfaces (i.e., sand or track). Using a wide pace range that encourages variation in gait parameters may also assist in distributing Achilles tendon loading. Pronation appears not to be associated with this increased stiffness and therefore correcting pronation with posted shoes or orthotics should be viewed with caution as this may increase stiffness and therefore injury risk in athletes. Gait retraining to reduce braking forces or increase knee and ankle rotation during stance may be beneficial for some athletes. However, reducing stiffness may be detrimental to performance.

6 Conclusions

There have been few studies examining the link between Achilles tendon injuries and lower extremity stiffness. Those that have, included stiffness as part of a screen of multiple biomechanical factors rather than looking at stiffness as a holistic measure that summarises how the limb or joint is functioning as a unit [119–121]. There is a potential link between the various measures of stiffness and risk of developing an Achilles tendon injury, which needs to be investigated further with studies designed to specifically address this question. All joints need to be assessed together to understand how they work together to create the healthy or injury-promoting environment.

The review aimed to identify whether there was a link between previously identified risk factors for Achilles tendon injuries and measures of lower leg stiffness. Combining the results to give an overview of the link between different Achilles tendon injury risk factors and stiffness was made difficult by the diversity of methods, models and magnitude of variable changes used. We cannot say conclusively that factors that increase the risk of Achilles tendon injuries also increase lower body stiffness; however, the trend of the results appears to suggest this. Increased propulsive and vertical force, and increased arch height, while protective for Achilles tendon injuries, also increased stiffness levels. Other factors (e.g., pronation) widely believed to be involved in increased risk of Achilles tendon injuries, were associated with decreased stiffness during running. Further longitudinal investigation into whether higher lower extremity stiffness is associated with increased risk of Achilles injury is needed. If a link between stiffness and injury is identified, then the next step will be to identify the exact causes of increased stiffness and injury risk, for example, tendon stiffness, muscle strength or coordination. Variability of stress to better distribute the load on the muscle–tendon unit is needed.

Clinicians should investigate the amount of high intensity or speed work and running on soft surfaces that an athlete has incorporated into training, in those presenting with a new or reoccurring Achilles tendon. Advice to limit speed work and running on surfaces such as sand may be helpful for these individuals; however, it may increase the risk of sustaining other injuries. It should be noted that increasing stiffness is associated with improved running performance; therefore, there may be a trade off between injury risk and performance which should be addressed on an individual basis.

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Compliance with Ethical Standards

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Conflicts of interest Anna Lorimer and Patria Hume declare they have no conflicts of interest relevant to the content of this review.

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