EVALUATING STIFFNESS OF THE LOWER LIMB ‘SPRINGS’ AS A MULTIFACTORIAL MEASURE OF ACHILLES TENDON INJURY RISK IN TRIATHLETES

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ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made in the acknowledgements.

Chapters 2 to 8 of this thesis represent separate papers that are either published or are to be submitted to peer-reviewed journals for consideration for publication. My contribution and the contribution by the various co-authors to each of these papers are outlined in the “candidate contributions to co-authored papers” table. All co-authors have approved the inclusion of the joint work in this PhD thesis.

Anna Lorimer

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CANDIDATE CONTRIBUTIONS TO CO-AUTHORED PAPERS

Chapter 2 Lorimer, A., Hume, P.A., Pearson, S. Retrospective injury NZ elite triathletes. To be submitted to *New Zealand Journal of Sports Medicine.*	Lorimer 80%, Hume 10%, Pearson 10%
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"We should not judge people by their peak of excellence; but by the distance they have travelled from the point where they started." — Henry Ward Beecher

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Ethical approval was granted by Auckland University of Technology Ethics Committee (AUTEC). The ethics approval references were:

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- 12/332 Sports Performance research institute New Zealand (SPRINZ) Clinics database. Approved 17th June 2013. The SPRINZ clinics database was used for Chapter 2: Retrospective injury NZ elite triathletes.

- 11/94 Reliability of stiffness measures for running. Approved on 3rd June 2011. Ethics approval covered Chapter 5: Comparison of methods for quantifying stiffness and their reliability in triathletes; Chapter 6: Lower limb stiffness is affected by running pace in triathletes; and Chapter 7: Reliability and variability of lover limb stiffness with changes in running pace for triathletes

- 11/276 Identifying risk factors for Achilles tendon injuries in triathletes. Approved on 12th December 2011. Ethics approval covered Chapter 8: Influence of prior cycling on lower limb stiffness in triathletes; and Chapter 9: Lower limb stiffness for the prediction of Achilles tendon injuries in triathletes: A prospective study.

ABSTRACT

Achilles tendon injuries were identified as problematic for New Zealand High Performance athletes by Triathlon New Zealand. Analysis of six years of injury data for New Zealand high performance triathletes indicated that Achilles tendon injuries (17%) were among the most common overuse lower limb injuries together with calf injuries (17%). The majority of injuries were attributed to running. These results correspond to injury analysis of British elite triathletes with reported high prevalence of Achilles tendon injuries in Olympic distance athletes. The exact mechanism of injury and what causes the pain is still unclear. However the reoccurring nature of the injury and often prolonged recovery times signal a need for the development of preventative interventions.

The main aim of the thesis was to determine whether a single measure can be used to identify individuals at risk of Achilles tendon injury. This was achieved through a series of specific questions which followed the Van Mechelen and Finch models for injury prevention research. The thesis was able to address, the extent of the problem, what is understood about the problem and make a unique contribution to understanding the mechanism of injury.

Individual risk factor analysis for Achilles tendon injuries via a systematic literature review resulted in only five risk factors that were clearly associated with injury. Increased braking force was associated with increased injury risk, while increasing surface stiffness, high arch height, large propulsive force and large vertical force were associated with decreased injury risk. Various other risk factors were also found that did not show clear effects. The slow progressive nature of overuse injuries suggests that the changes in loading to the tendon are subtle and therefore, individual risk factor analysis is not likely to clearly determine the causative factors. Therefore, investigation of measurements that measure changes in movement patterns may provide greater insight. Stiffness was found to be increased in the leg and decreased in the ankle for athletes who had prior Achilles tendon injuries compared to uninjured controls. Lower limb stiffness is a measure of how the joints work in relation to one another to absorb impact upon contact and reflect the synergistic activity of muscles, tendons and ligaments. Stiffness therefore may provide a useful measure of looking at the landing movement as a whole and provide information regarding injury risk.

The influence of the different risk factors, that were identified to have a definite or possible role in Achilles tendon injury risk, on lower limb stiffness were therefore investigated via a systematic review. The majority of Achilles injury risk factors were associated with increases in lower limb stiffness measures, however the results were unclear. Based on the evidence, it was considered that stiffness was a potentially useful measure for analysing Achilles tendon injury risk and should be investigated further.

In a reliability laboratory study of 12 male triathletes, vertical and leg stiffness had good reliability as did ankle stiffness. Knee and hip stiffness reliability were moderate to poor, however combining the knee and ankle improved the reliability. Knee and ankle stiffness appeared to have the greatest contribution to leg stiffness.

The effect of different training conditions on lower body stiffness measures were investigated in 75 triathletes. The effect of increasing running pace on the different lower limb stiffness measures was dependent on the magnitude of the increase in velocity and the starting pace. Vertical, knee and ankle stiffness increased with increasing running pace. Leg and hip stiffness were largely unaffected by changes in pace. It was hypothesised that the different joints had varying levels of importance in modifying stiffness to stabilise gait depending on whether pace was increased by increasing stride length or decreasing contact time. Further investigation of how changes in the temporal and spatial parameters of an athlete's running gait influence lower limb stiffness may provide insight into both injury risk and how stiffness can be modified in at risk individuals.

A useful screening tool would be adaptable to the requirements of the athlete. Therefore, stable reliability over a range of paces would be ideal. Reliability of vertical and leg stiffness remained unchanged over the pace ranges measured. Combined knee and ankle stiffness had acceptable reliability over all paces. Between subject variability was largely unaffected by increasing running pace suggesting a similar pattern of stiffness adjustment within the group. Outliers from this pattern of adjustment may provide insight into injury risk. Within subject variability for the knee and ankle demonstrated a slight 'U-shaped' pattern highlighting the need for athletes to utilise a wide range of running paces during training in order to maximise gait variability for injury prevention. Extremely high variability may indicate a pace at which coordination is unable to be maintained and prolonged periods at this pace should therefore be established gradually.

In triathlon, the cycle to run transition is widely thought to be associated with increased injury risk. Running following a 30 minute self-paced cycle did not appear to alter stiffness substantially in a laboratory based study of 34 triathletes. Leg and ankle stiffness showed small increases in the first minute of running after cycling compared to isolated running. Individual responses were apparent within the group, with the most notable being either an increase in ankle stiffness but a decrease in knee stiffness in the first four minutes of running. An opposite change in stiffness between the knee and ankle may indicate an uncoupling of normal gait coordination which could be related to an increased risk in injury. Further research into the relationship between gait parameters, running economy and stiffness is required in order to understand the differences between responding and non-responding athletes.

After baseline screening for stiffness measures, 75 triathletes were followed for a year via on-line weekly reporting of training and injury information. Eight Achilles tendon injuries were reported during this time. Using an intention to treat analysis, individuals who had experienced an Achilles tendon injury either prior to the study or during the surveillance period had reduced ankle stiffness compared to uninjured triathletes. Leg stiffness was increased in triathletes who developed an Achilles tendon injury during the surveillance period, and knee stiffness was increased in triathletes who developed their first Achilles tendon injury during the study, compared to uninjured athletes. A new measurement, the knee-ankle stiffness ratio, was developed which may be able to predict triathletes who will go on to develop an Achilles tendon injury. Athletes at risk of developing Achilles tendon injuries had a higher knee stiffness compared to ankle stiffness, while those who did not develop Achilles injuries had similar stiffness at the knee and ankle during running.

The knee-ankle stiffness ratio needs to be further investigated to determine the mechanism of the imbalance and what interventions can be used to reduce the stiffness difference. The knee-ankle stiffness ratio may provide a useful measurement for identifying triathletes and perhaps other running athletes who are at risk of developing Achilles tendon injuries in the future.

CHAPTER 1

INTRODUCTION, RATIONALE FOR THE STUDIES BASED ON CRITIQUE OF THE LITERATURE, AND STRUCTURE OF THE THESIS (PREFACE)

Defining the issue

Overuse injuries are of significant concern to triathletes with prevalence reported as between 60 and 89% (1-18). Diversity of injury definitions and injury site reporting in previous research makes comparisons difficult (7). General trends are that tendinopathies and muscle strains have been the most commonly reported injuries in retrospective studies of both amateur and elite triathletes (5, 9, 15, 16). The knee, back and Achilles tendon are the most common body site of pain causing reduced or halted training (9, 10, 16). Achilles tendon overuse is the most severe based on the number of training days lost (16). Treatment methods remain speculative with little understanding as to why some individuals respond and others do not (19, 20). Resolution of Achilles tendon overuse symptoms does not guarantee full recovery of musculotendinous function (21) and reoccurrence of pain and reduced function is common. Therefore, the development of preventative interventions to reduce the development of Achilles overuse injuries is important.

Within New Zealand’s Olympic distance triathlon high performance squad, 5/21 triathletes reported Achilles complaints in 2011 (pers. comm.). New Zealand’s two most prominent Ironman triathletes, Terenzo Bozzone and Cameron Brown, both took time out from training and racing in early 2011 due to Achilles tendon injuries. Maintaining or improving performance on the world stage is dependent on the ability to sustaining rigorous training and build on the previous year’s endurance and speed. Therefore, any prolonged absence from training can be detrimental to immediate and long term performance. Prevention of injuries is a priority in all sporting codes to assist with athlete success. Understanding the mechanisms of injury and development of preventative methods is of concern for High Performance Sport New Zealand (HPSNZ) and served as the motivation to undertake this thesis.

Methodological approach to the issue

Triathlon has had a short but precipitous introduction into the sporting world. From its tentative and unstructured start in the early 80s, triathlon had gained Olympic sport status by the Sydney 2000 games. Triathlon has expanded rapidly at elite and amateur levels and attracts many individuals from other sports due to the cited benefits of cross training (22). With the attainment of Olympic status, the dynamics of triathlon changed significantly. Drafting in cycling was allowed leading to an increased emphasis on running ability emerging for elite Olympic distance races. Amateur and longer distance races do not allow drafting so the complexity of triathlon has increased with race strategies and training become more diverse.

The rapid expansion and changing nature of the sport has resulted in a significant gap in the understanding of triathlon injuries. While, injury analysis from the contributing individual sports can give some insight, high intensity training for three sports, reduced rest time and transitioning between different sports has added an additional layer of complexity.

In the study of sports injury and injury prevention, Van Mechlen (23) described a four stage model framework: stage 1 – Injury surveillance; stage 2 – Aetiology and mechanism of injury determination; stage 3 – Development and introduction of preventative measures; stage 4 – Evaluation of prevention effectiveness. Finch (24) developed the framework further specifying the introduction of the preventative intervention in a controlled ideal environment in stage 3 and 4 and introducing a further two stages: stage 5 – Understanding of the intervention context in the real world and adapting to accommodate; stage 6 – Evaluation of the intervention in the real world. Gosling et al. (7) reviewed the progress of triathlon injury research in the Translating Research into Injury Prevention Practice (TRIPP) (24) framework highlighting several issues and gaps in the current knowledge. Stage 1 lacked consensus on injury definition, site and severity reporting, and had variability in duration of injury surveillance, and limitations given the retrospective nature of the majority of research (7). Stage 2 had confusion over the causative activity, ambiguity between cause and mechanism, lack and variability of injury definitions, lack of prospective studies for risk factor analysis, a limited number of risk factors formally investigated, differences in population groups, and insufficient sample sizes. Stage 3 had a longer distance event focus, single event studies, focus on secondary and tertiary interventions (lack of primary), and a lack of formal investigation into primary interventions (7). Published research focused on stages 4 to 6 is currently non-existent.

Studies specific to Achilles tendon injuries in triathletes are currently absent from the literature. Injury research has focused on overuse injuries collectively resulting in many identified risk factors and few answers.

The thesis research therefore investigated the issue of Achilles tendon injuries in running athletes with specific focus on triathletes. Using the Van Mechelen model (23) as a guide, the approach was to evaluate the New Zealand triathlon injury data, review the literature, and then to examine risk factors from a biomechanical perspective in triathletes via laboratory based studies. The multifactorial nature of overuse injuries suggested the need to study movement patterns rather than individual risk factors.

The aim of the literature reviews was to first identify all the individual risk factors that have been identified. From these only one measure was identified that incorporated the function of multiple joints and tissues, stiffness. The second literature review therefore looked at the effect of the individual risk factors on stiffness to determine whether this measure was multifactorial with regards to biomechanical risk factors for Achilles tendon injury and the changes in stiffness expected in triathletes with increased injury risk. The literature reviews identified stiffness of the lower limb as a potential measure which incorporated many identified Achilles tendon injury risk factors. Several methods are available for measuring lower limb stiffness, therefore the subsequent laboratory based studies were developed to identify the best way of measuring stiffness. It is important to understand how different environmental and task constraints alter a measurement in order to make recommendations for reducing risk. Stiffness changes with increasing running pace and the transition from cycling to running was therefore investigated. Baseline screening of triathletes' lower limb stiffness was conducted followed by one year of injury surveillance. Figure 1 outlines the thesis chapters resulting from the epidemiology review, literature reviews, laboratory testing and on-line prospective injury data collection.

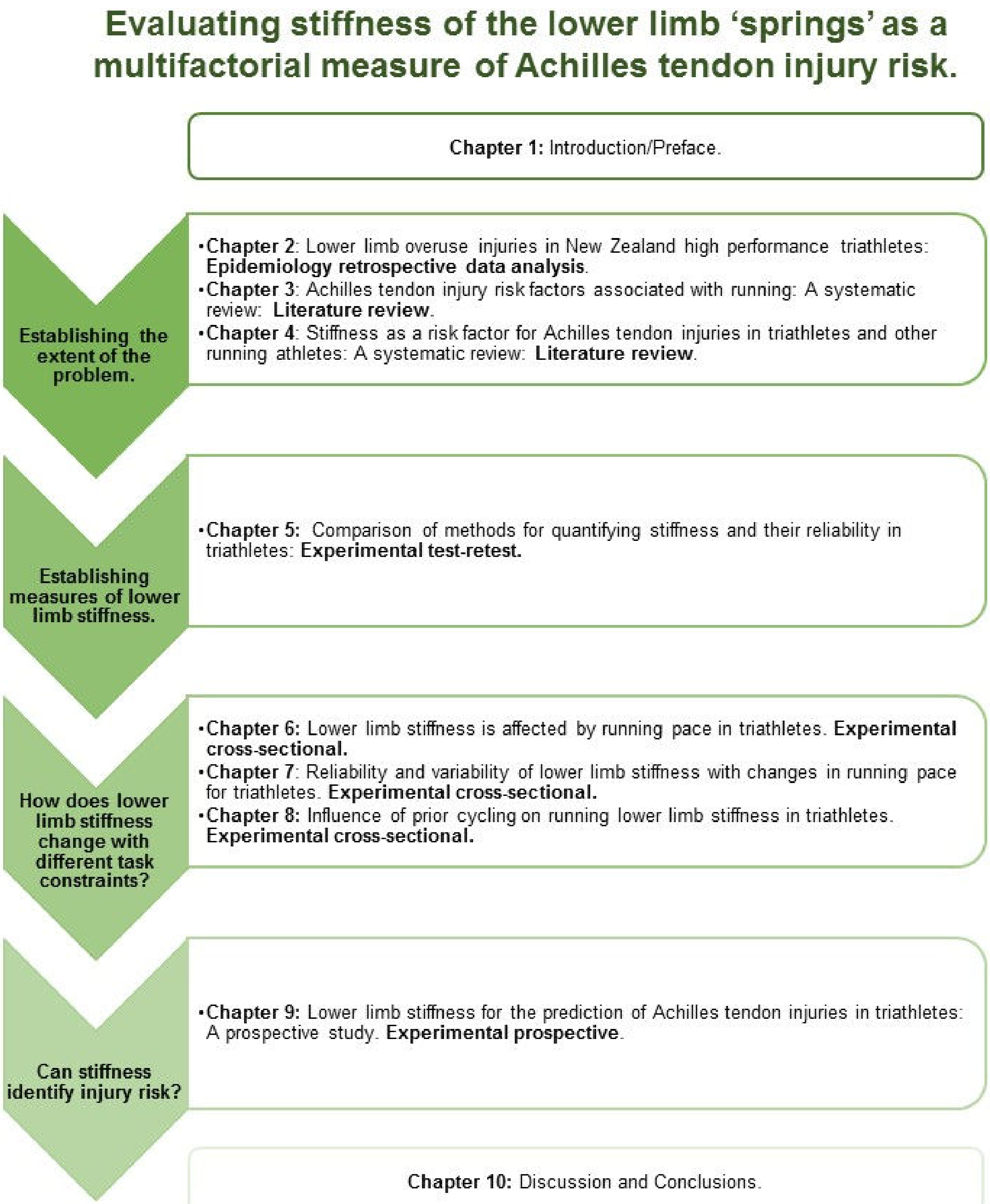

Figure 1.1: Flow of thesis themes and chapters

Establishing the extent of the problem

Chapter 2: Lower limb overuse injuries in New Zealand high performance triathletes: Epidemiology retrospective data analysis.

In a literature review of the epidemiological evidence for triathlon, 32 studies were identified of which 22 were retrospective, and only four were prospective or contained a prospective component in the research (14). Duration of the surveillance ranged from a single race, race series or eight weeks up to the athlete's entire career. Individual races tended to be focused on the effects of heat and associated medical conditions (14). Recent research into musculoskeletal injuries has been on British, Australian, Japanese and European triathletes (2, 9, 11, 13, 16, 25-27). When Achilles tendon injuries have been isolated within the injury location definition, they have featured amongst the most common injuries (4, 12, 16, 18, 27, 28). Up to 50% of British Olympic distance and 10% of British Ironman distance triathletes suffered from Achilles injuries (16). Whether New Zealand athletes showed a similar risk profile was only supported by anecdotal reports. Chapter two reports our investigation of the extent of the problem over the past six years in New Zealand's elite and development triathlon squad. Achilles tendon injuries and calf injuries were the most common injuries, accounting for 17% each of all lower limb injuries reported. Prevention of Achilles tendon injuries is clearly required.

Stage two of the injury prevention model (23) focuses on understanding the mechanism of injury. Research into tendon injuries is diverse and inconclusive covering aspects from cell biology up to whole body analysis. In order to understand how triathlon training and racing could result in tendon degeneration, tendinopathy at a tissue level was investigated. The key findings are presented here in the introduction.

The Achilles tendon is the largest and strongest tendon in the human body and plays a key role in running and jumping movements (29, 30). From a mechanical view the Achilles tendon design is optimised to withstand high tensile forces (30). The broad, flat aponeurosis and enthesis provide multiple and highly adapted points of attachment to the muscle and bone (31, 32), while the narrow, rounded mid-portion distributes the load across the width of the structure. Despite this design, the Achilles tendon is one of the lead causes of lower leg pain and loss of function in athletes utilising repetitive stretch-shorten cycle (SSC) activity (33, 34).

Achilles tendon properties

The Achilles tendon is largely composed of collagen fibres extending from the three muscles of the triceps surae – medial gastrocnemius, lateral gastrocnemius and soleus – to the calcaneus, with approximately 50% of fibres derived from the soleus (30). The tendons mechanical properties are derived from its biochemical composition. Up to 85% of the dry weight is collagen, primarily strong Type I fibres which are held together with non-reducible cross-links for tensile strength. The 2% dry weight elastin content allows extensibility and return of the structure when stretched within physiological levels and a specific profile of glycosaminoglycans (GAGs) and proteoglycans contribute to the water content, viscoelastic and loading profile (35). The characteristic load deformation profile has four regions: the toe region accounting for straightening of the crimp and alignment of fibres; the linear region where slope is equal to stiffness; microscopic failure of individual fibres; and finally macroscopic failure or rupture (36, 37). The primary cell type in tendons are the tenocyte, long, spindle shaped cells which align along collagen fibrils and are metabolically active, continuously remodelling the tendon to adapt to load (38).

Mechanism of injury

The mechanism of Achilles tendon injuries remains under debate, however a number of risk factors have been identified, including the extrinsic factors (running surface, shoes, training error, running technique and previous injury) and intrinsic factors (age, gender, genetics, gastrocnemius dysfunction, muscle weakness and lower limb alignment) (39). Over pronation or prolonged pronation has long been associated with Achilles tendon injuries (40-42). Without large prospective studies however, the contribution of these risk factors to the underlying tendon pain and degeneration cannot be determined.

Combining biomechanical, biochemical, mechanobiology and immunobiology research, the current theories for the mechanism of tendon degeneration can be summarised as 'non-homologous loading' over prolonged periods causing tissue degeneration (43). There are four loading stimuli the tendon can be exposed to: tensile, shear, compressive and thermal. Compressive loads have been implicated in some forms of tendinopathy (44, 45), however are unlikely to be involved in cases of Achilles injuries in triathletes.

Tensile loading

The precisely organised structure of the tendon allows it to withstand extreme tensile loads at the attachment sites to bone (30, 31) and muscle and along its length. In vitro testing of human Achilles tendon specimens found failure load, stress and mid-substance strain to be 5098 ±1199 N, 79 ±22 MPa and 8.8 ±1.9% respectively (46). Early modelling studies calculated a peak force during stance phase of running for a single individual to be 3100 N or 6.3 BW with a range of 6.1-8.3 BW over five trials (47). Using a tendon cross sectional area of 0.5 cm^2 peak stress was calculated as 62 MPa (47). Using buckle transducers attached directly to the tendon, peak stress was recorded as high as 111 MPa during running (48). Recent advances in ultrasound have enabled non-invasive, in vivo measurement of tendon mechanical properties. Non-weight bearing measures of peak free Achilles tendon force, stress and strain during maximal voluntary isometric contractions were 2011 N, 31 MPa and 4.5% respectively (49). During the higher impact activity of single leg hopping, Achilles tendon forces approached 5000 N giving strain values of 6.2-10.3% (50). Therefore, while it is thought that physiological loading, generally stays below the rupture threshold, it is possible that tensile loads can approach damaging levels. In vitro values should be compared to in vivo loading with caution due to the differences in the mechanical environment of the tendon.

The rate of loading also influenced the threshold values with a 10% increase in strain rate from 1 to 10% s^{-1} caused a 15% increase failure stress and strain (46). Activities such as running and hopping, with higher strain rates would therefore be expected to have a higher failure stress and strain, so it is possible that even the high values measured are still within the safe loading range. The safety margin for the Achilles tendon however is much smaller than for other tendons (51).

Achilles tendon injuries in triathlon are frequently not the result of rupture but gradual degeneration of the tendon. Macroscopically, chronically painful Achilles tendons change from glossy white tendon to a dull yellowish colour (52). Histopathological examination reveals areas of disorganised collagen fibres, increased GAGs and proteoglycans (53-55). Tenocyte numbers are increased, taking on a more rounded cell shape and nuclei, indicative of increased metabolic activity. Alternatively, numbers can be decreased, with characteristics signs of apoptosis (53-55). Immunohistochemistry has shown that type III collagen, GAGs and water content are significantly increased (56).

Results in the literature vary, however changes in gene expression have been observed. An inversion of the ratio of the proteoglycans, aggrecans and biglycans has been reported (57, 58) with an elevation of the fibrocartilagenous aggrecans. An increase in expression of fibronectin, collagen III and hyaline cross-links also indicates fibrotic repair (53, 56, 59). The normal tendon repair response involves laying down of weaker collagen III fibres which are then slowly converted to type I collagen and aligned along the axis of strain (60). The enzymatic profile of the tendon also changes with a down-regulation of the matrix metalloprotease (MMP) -3 which plays a role in tendon remodelling with collagen III, fibronectin and proteoglycans as specific substrates (53, 56, 61). Breakdown of collagen I is controlled by MMPs -1 and -13 which have elevated expression and/or activity in tendinopathic tissue (56, 61). It is unclear whether this profile indicates a failed repair response or a pathological response such as elevated scar formation.

As a metabolically active tissue, tendon cells are constantly responding to chemical messages and changes to the environment. Mechanobiology studies have shown that different types of forces result in different gene expression profiles (62). These observations have given rise to the stress shielding theory. Depriving rat tail tendons of their homeostatic resting tensile load resulted in an inversion of the ratio of MMP-13 and tissue inhibitor of metalloproteases (TIMPs) -1 from 1:3.75 to 1:0.25 (63). Rat MMP-13 has a similar activity and substrate profile to human MMP-1 (61). Stoichiometrically, TIMPs act as inhibitors of MMPs, therefore this ratio change would result in increased MMP-13 activity (63). Cyclic loading of the tendon resulted in a small dose dependent reversal in the effect (63). Induction of local fibrillar damage within an intact rat tail tendon via tensile loading recreated these results but gene expression and protein level increases of MMP-13 were only found localised to the area of damage (64).

Modelling and loading studies have shown that immobilisation causes a significant decrease in the modulus, cross-sectional area and strength of a tendon, changes which can be reversed with remobilisation (44). From such observations has come the theory of mechanostat; that is that individual tissues have a set point for which mechanical loading above or below results in anabolic or catabolic metabolism, respectively (65). Using the rat tail tendon model it was shown that fresh excised tendons only required 1% strain cyclic loading in order to inhibit increased MMP-13 activity (66). However, stress shielding for 24 hours resulted in a change in the mechanostat set point, requiring loading of 3% strain to produce the same level of MMP-13 inhibition (66).

The argument behind stress shielding as a mechanism of tendinopathy is that uneven strain across the tendon, due to differing force levels within the muscle or between the three muscles of the triceps surae results in isolated areas subjected to strain above the rupture threshold (67). Isolated collagen fibril rupture then causes a localised up regulation in catabolic enzymes and degeneration of surrounding tissue. With a new mechanostat set point, a greater loading stimulus would be needed in order to halt or reverse this process (67). The result of tensile strain resulting in focal damage is a weaker tissue, whether this is due to remodelling to adjust for detected load or scar formation in the process of repair. If loading then occurs the tissue is more susceptible to damage and a cyclic process of progressively weakening tissue results.

Shearing

Intratendinous shearing has been suggested as an alternative means of overloading the tendon leading to tendinopathy (68). Collagen fibres are not of themselves extensible. Elongation of the tendon results from straightening of the crimp in the fibres and aligning of the collagen fibres at low strain levels (2-4%) (69). At higher strain levels the collagen fibres move past one another and draw together exuding water, which results in a narrower but longer structure creating increased shearing between the fibres with increasing elongation (69). Strain has been shown to change in the medial and lateral portions of the distal Achilles tendon with calcaneal motion, eversion significantly increasing medial strain and inversion, lateral strain (70). The evidence suggests, that forces act along different planes, torsional versus tensile, which would create shearing stress at different angles to the collagen fibre orientation.

Angle of shear compared to fibre orientation has been shown to be important in determining the amount of stress that a biological tissue is exposed to (71). A model incorporating the mechanical features of collagen fibres and a lattice of collagen fibres aligned as in tendons indicated a narrow band around zero angle (direction of fibre orientation) where unlimited shearing is possible. Shearing occurring at angles outside of this band resulted in increased stress on the tissue with the greatest stress occurring at angles of 30 and 45^0. Hydrostatic stress shows a similar response with stress being greater at angles different from fibre orientation.

Intratendinous shearing is also influenced by the muscle action. Anatomy, muscle compartments, muscle recruitment strategies and force transmission pathways all contribute to the uniformity of muscle activity and the strain transferred to the tendon (72). The gastrocnemii and soleus contribute to the strain transferred to the Achilles tendon. Fascicle length of the lateral gastrocnemius is longer however the pennation angle of the medial gastrocnemius is greater and results in a larger cross sectional area and force production capability (73). Gastrocnemius insufficiency results in significant differential displacement of the soleus and gastrocnemius aponeuroses depending on the angle of the knee joint, highlighting the extent of intratendinous shearing (74).

Thermal

During gait the Achilles tendon plays a critical role in energy storage and return, reducing energy expenditure by contributing up to 53% of the positive work at the ankle (75). However, tendons are not perfectly elastic and significant energy loss in the form of heat (hysteresis), up to 20% has been reported (50). Wilson and Goodship (76) developed a model to calculate, in vivo, the tissue temperature resulting from tendon hysteresis in equine superficial digital flexor tendons (76). Using measured tendon force, stiffness and hysteresis, the average temperature of the human tendon was estimated to be 41.4^0 C, range 38-44^0 C (75). Exposure of tenocytes to 41^0 C for 10 minutes resulted in 10% cell death. Survival is reduced with longer exposure or higher temperatures. It is therefore possible that temperatures in excess of 41^0 C for prolonged periods, as seen in endurance sports, could result in significant cell death. Alternatively, repeated bouts of non-fatal hyperthermia could disrupt tendon metabolism leading to degeneration. Tendon stiffness and level of strain were found to contribute to hysteresis. Increased strain causes an increase in tendon temperature while stiffer tendons experience lower hysteresis (75).

Risk factor analysis

The tissue level examination of Achilles tendon injuries indicated that overuse injuries were the result of uneven tensile, shearing or thermal loading. Some runners can support high training loads without injury. Therefore, uneven loading is likely the result of some modification in movement. A review of the current biomechanical risk factors associated with Achilles tendon injuries was therefore conducted.

Achilles injury research above the cellular and tissue level has focused on identifying risk factors related to injury. Retrospective studies are limited to training, equipment, demographic and structural alignment variables. Epidemiological studies have shown that while the general population suffer from Achilles tendon injuries, the incidences are significantly higher in athletes (77, 78). Sports related chronic injuries of tendons are understood to be the result of repetitive loading at the joint over which the tendon acts. However, loading levels and repetitions alone are not sufficient to explain why a particular athlete is susceptible. The biomechanics of the athlete also plays a role.

The multifactorial nature of overuse injuries explains the disparity in the literature regarding isolated variables and the lack of conclusive mechanisms of injury. Human movement is highly variable allowing a goal to be achieved by a variety of routes or methods. The routes to injury are likely also varied and diverse. Therefore, while individual risk factor analysis sheds some light, a more holistic approach may prove more successful in analysing an individual's risk of injury. Two reviews of literature were therefore completed to gain insight.

Chapter 3: Achilles tendon injury risk factors associated with running: A systematic review: Literature review.

Chapter 3 focuses on risk factors and mechanisms of Achilles tendon injury in running athletes via a systematic review. SPORTDiscus, CINAHL, Web of Science and PubMed were searched for Achilles tendon injury risk factors and biomechanical measures which are altered in runners with Achilles tendon injuries, excluding ruptures. Fifteen articles were included in the analysis. Two variables, high vertical forces and high arch, showed strong evidence for reduced injury risk. High propulsive forces and running on stiffer surfaces may also be protective. Only one biomechanical variable, high braking force, showed clear evidence for increasing Achilles injury risk.

Only five variables, out of the many investigated, showed a clear association with Achilles tendon injury. The nature of overuse injuries, however, suggests that any differences in movement that lead to injury will be small. The nature of movement results in low variability for the endpoint or gross movement (79). However, variability for the individual joint and segment movements that make up the gross movement can be large (79).Therefore, any small differences in single risk factors, such as rearfoot eversion, are likely to be lost in large group variability. Stiffness has been suggested to be associated with injury risk (80). Leg stiffness was found to have a potentially large, negative effect on tendon health while ankle stiffness was potentially beneficial. Stiffness was also noted to be associated with a number of other identified risk factors. Stiffness, was therefore identified as a measure that may identify faulty movement patterns leading to injury where single joint and muscle strength analysis had failed.

Chapter 4: Stiffness as a risk factor for Achilles tendon injuries in triathletes and other running athletes: A systematic review: Literature review.

Chapter 4 therefore focused on identifying which of the risk factors from chapter 3 altered stiffness and in what way stiffness was altered. As triathletes were the target athlete group, risk factors specific to them (i.e. transitioning from cycling to running) were also considered. Databases PubMed, SPORTDiscus, CINAHL and Web of Science to November 2013 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; gender. Stiffness measurement studies using the oscillation technique, quick release or ultrasound were excluded. Increased braking force and low surface stiffness were definitely associated with increased risk of Achilles tendon injuries and resulted in increased lower body stiffness. High arches and increased vertical and propulsive forces, however, were found to be protective for Achilles tendon injuries and were also associated with increased lower body stiffness. Risk factors for Achilles tendon injuries that had unclear results were also investigated with the evidence trending towards an increase in stiffness being detrimental to Achilles tendon health.

The large number of different methods for measuring stiffness and the large range of variable changes that were used made combining the results difficult. While we could not conclusively say that factors associated with increased risk of Achilles tendon injury resulted in increased stiffness measures, the overall trend of the data suggested this. Lower body stiffness was therefore identified as a potential measure for screening athletes for Achilles tendon overuse injury risk. Further research into this measure and its impact on tendon health is warranted.

Establishing measures of lower limb stiffness.

This section of the thesis used an experimental approach.

Chapter 5: Methods of quantifying stiffness and their reliability in triathletes: Experimental test-retest.

There have been a number of methods and equations reported for the calculation of vertical, leg and joint stiffness. The reliability of these measures and how each measurement and method compares is a useful tool for the researcher when determining which method to use in assessing an athlete, given the constraints of the measurement environment. Vertical stiffness measures how the body responds to contact with the ground as a function of the vertical oscillation of the centre of mass (COM). Changes in COM displacement occur through compression of the 'leg spring' which is controlled by leg stiffness. Compression of the 'leg spring' is the result of joint rotation. While joint stiffness holds the greatest detail regarding the mechanics of landing during hopping or running, research into the contribution of each joint remains contentious and limited. The hip joint is also often ignored despite this being the fundamental connection of the “leg spring” to the body mass. The hip joint is key in determining the angle of the leg swing and performance indicators such as stride length and velocity. A better understanding of how each joint contributes to the compression of the “leg spring” and how these vary between subjects and conditions would provide insight into the different routes by which movement and/or injury are achieved. Therefore Chapter 5 was a test-retest experimental study of 12 competitive, male age group triathletes.

On two occasions, seven days apart, triathletes ran on a motorised treadmill at four different paces (5.5, 5.0, 4.5 and 4.0 min/km) for two minutes each. Kinematic and kinetic data were collected using a 9-camera Vicon 3D motion capture system with Bertec instrumented treadmill. Athletes then hopped in place at 2.2 Hz on the treadmill (for force data). Ten consecutive hops with a normal bent knee and 10 hops with a straight knee were collected. Stiffness was calculated for ten consecutive steps on each leg during the running trials and five consecutive hops and then averaged. Test-retest reliability was determined from the results of four measures (percentage mean difference, effect size, coefficient of variation (%) and intraclass correlation coefficient). Pearson’s correlations were used to compare vertical and leg stiffness and leg and joint stiffness as well as hopping with running. Hopping was found to be a poor surrogate for running stiffness when confined to 2.2 Hz. The dynamic and time stiffness measures gave the best reliability and also showed the best correlations with joint stiffness. While ankle stiffness showed acceptable reliability, the hip and knee did not. However when the joints were combined as sum of all three joints, sum of hip and knee or sum of knee and ankle then reliability was improved. The knee + ankle combination was best correlated with leg stiffness. The knee and ankle therefore appear to have the largest influence on leg stiffness.

By using a combination of the joints as well as the joints in isolation, a reliable method for assessing joint stiffness was identified. These stiffness measures were then used in the following chapters to investigate the potential for stiffness as a measure to predict risk of developing an Achilles tendon injury in triathletes. Changing the task or environment constraints alters lower limb stiffness, highlighted in chapter four. An understanding of how stiffness is changed under different conditions experienced by the athlete’s in question is important for understanding injury and making recommendations for minimising risk. Two different constraints experienced by triathletes is changes in velocity during training and racing and running following fatiguing cycling.

How does lower limb stiffness change with different task constraints?

The next section of the thesis took an experimental approach with data collection in the laboratory. The effect of increasing running pace and transitioning from cycling to running were investigated. These task constraints were measured in the controlled laboratory environment with three dimensional motion capture and force. The response of the individual athlete to changes in these conditions provided insight into why some athletes are more likely to sustain Achilles injuries.

Chapters 6, 7 and 8 were based on an experimental study of 75 elite and competitive age group triathletes completing a stepped treadmill run protocol. Triathletes were marked for three dimensional motion capture and then ran for two minutes each at 5.5, 5.0, 4.5 and 4.0 min/km following a five minute warm-up at 6.0 min/km (Chapters 6 and 7). Thirty-seven triathletes returned after approximately six months for the transition assessment (Chapter 8). After repeating the graded run protocol to give isolated (IR) run stiffness values, triathletes cycled for 30 minutes on a wind trainer. Stiffness was recorded every minute for the first ten minutes of the following steady paced run and every two minutes for a further 10 minutes.

Chapter 6: Lower limb stiffness is affected by running pace in triathletes. Experimental cross-sectional.

Vertical, knee and ankle stiffness increased with increasing pace, while leg and hip stiffness were largely unaffected. Leg stiffness showed small decreases for the 5.5-5.0 min/km and the 5.5-4.5 min/km pace increases. The magnitude of the vertical, knee and ankle stiffness changes were dependent on the starting pace and the size of the velocity increase. It was hypothesised that leg, knee and ankle stiffness changes were dependent on the mechanism by which running pace was increased, either increasing stride length or decreasing stride rate. The mechanism by which an athlete increases running pace influences the balance between knee and ankle stiffness, with each joint increasing following an independent pattern. Therefore, pace changes may alter the balance between knee and ankle stiffness in some athletes increasing either shearing or torsional loading within a portion of the Achilles tendon, increasing injury risk. The independent changes in stiffness for the different joints lead us to consider how stiffness is controlled during running and an investigation of how within and between athlete variability is affected by pace changes.

Chapter 7: Reliability and variability of lower limb stiffness with changes in running pace for triathletes.

A screening measure needs to be adaptable to the requirements of the specific athlete and therefore reliable over a range of conditions. Reliability of the stiffness measures were therefore investigated over the four tested running paces in 12 athletes using a test-retest experimental approach. Reliability of vertical and leg stiffness was unaffected by increasing running pace and combined knee and ankle stiffness gave acceptable reliability across the range of paces tested. Therefore, lower limb stiffness would make a useful screening tool for athletes of a range of abilities and distance specialities.

Traditional movement analysis viewed movement variability as noise or even potentially injurious. Movement variability allows an individual to adapt to changes in the task and environmental constraints reducing injury risk. Movement variability also distributes loading of repetitive movements over a range of tissues, possibly reducing the risk of overloading and development of overuse injuries. Understanding the variability of movement patterns may be important in analysing injury risk. Between athlete stiffness variability remained relatively stable over the range of paces tested suggesting a group pattern of stiffness adjustment with increasing running pace. Identifying outliers from this pattern of adjustment may highlight individuals at increased risk of injury. The knee had the largest within subject variability highlighting its importance in the control of leg stiffness. A slight ‘U-shaped’ pattern was observed for the within subject knee and ankle stiffness variability highlighting the importance of incorporating different running paces in training in order to encourage gait variability. Extremely large variability however may be indicative of paces at which the athlete is unable to maintain coordination and therefore prolonged periods at such paces should be built up gradually.

Chapter 8: Influence of prior cycling on lower limb stiffness in triathletes. Experimental cross-sectional.

The most startling alteration in the task of running for any new triathlete is the transition from cycling to running. Athlete’s report a feeling of loss of coordination and the cost of running has been shown to increase compared to isolated running. It is believed that this ‘loss of coordination’ may be associated with an increased risk of injury. Vertical, leg and ankle stiffness showed small but unclear increases in stiffness following cycling compared to a matched pace isolated run. Differences were only apparent for the first one to two minutes. Individual analysis however showed that while most of the triathletes tested clustered around zero change, a number of triathletes showed distinct individual responses. The most interesting response was an increase in ankle stiffness and decrease in knee stiffness. The majority of changes to the task or environment constraints result in a simultaneous increase in both knee and ankle stiffness. The opposite response observed between the knee and ankle may indicate an uncoupling of the movement between the knee and ankle. Changing the balance between the knee and ankle stiffness may increase either shearing or torsional loading within the tendon increasing injury risk.

The findings from chapters 6, 7 and 8 led to the next stage of the thesis focused on whether lower body stiffness could help predict Achilles injury risk.

Can stiffness identify injury risk?

Chapter 9: Lower limb stiffness for the prediction of Achilles tendon injuries in triathletes: A prospective study. Experimental prospective.

While lower body stiffness during running addresses the need for a more holistic approach to the injury prevention problem, the ability to predict injury needs to be assessed through prospective analysis. The predictive value of lower limb stiffness for Achilles tendon injury was assessed through a one-year prospective study of 75 elite and competitive triathletes. Eight Achilles tendon injuries were reported during the study period of which three were a first occurrence. A further nine athletes reported having had a previous Achilles tendon injury but were not reinjured during the study period. Stiffness measures for the FirstAchilles, PriorAchilles and PriorUninjured groups were compared with the Uninjured group for the four paces of the graded run test. Leg stiffness was increased by a small to moderate effect size in the groups that developed an Achilles injury in the surveillance year. The pattern of knee and ankle stiffness lead to the analysis of a new measure, the knee to ankle stiffness ratio which showed a moderate increase in both the FirstAchilles and PriorAchilles group compared to the uninjured group. The PriorUninjured group on the other hand had no difference in the knee to ankle stiffness ratio compared to the uninjured group. The knee to ankle stiffness ratio therefore may be a measure that will enable not only the prediction of risk of an athlete developing an Achilles injury but also assessment of an athlete’s likelihood of suffering a reoccurring injury.

Chapter 10: Discussion and Conclusions.

The final chapter draws together the key findings from each of the prior thesis chapters and relates these finds to the current literature. Limitations of each study and implications for future research are provided. Practical applications are suggested, many of which have already been implemented by triathletes in New Zealand as a result of the thesis work.

While the analysis of joint stiffness is a more equipment and labour intensive measure than leg stiffness, the joints and how they work together provide a more comprehensive view of how the system is performing than leg or vertical stiffness. Leg stiffness with its ability to be utilised in the field may be useful as an initial screen flagging individuals who should then follow a more in depth screening process to determine joint stiffness balance and possible causes of any imbalances. The imbalance between knee and ankle stiffness could be the result of a number of contributing factors including gait parameters or muscular strength imbalances. By utilising an inversion of the traditional injury analysis process, looking at the movement more globally before working down to the individual problems we are left with more questions than answers. However, the balance between the knee and ankle stiffness during running has highlighted some exciting areas for future research.

The ability to predict an athlete's risk of sustaining an overuse injury is only the first step in being able to prevent the injury from occurring. As highlighted in the Van Mechlen framework, once mechanistic issues have been addressed the process of developing, testing and applying preventative interventions needs to be launched. Measuring the function and movement pattern of the athlete through stiffness, circumvents the issue of multiple causative factors clouding the overall risk, however it does not shed light on the mechanism of the increased risk. Therefore, before preventative interventions can be developed, analysis of the individual pathways leading to increased overall risk value needs to be undertaken. This research is the beginning of a far greater process leading to reduction in the number of triathletes afflicted by Achilles tendon injuries bringing both performance and economic benefits. All good things take time!

CHAPTER 2

LOWER LIMB OVERUSE INJURIES IN NEW ZEALAND HIGH PERFORMANCE TRIATHLETES

This chapter comprises the following paper:

Lorimer, A., Hume, P., Pearson, S. Lower limb overuse injuries in New Zealand high performance triathletes.

Overview

Background: Prevention of overuse injuries is of major concern for New Zealand's top triathletes, enabling consistent training gains to improve performance. However, the pattern of injuries in this population remains unclear as formal injury surveillance has not been carried out since the mid 1980's.

Aim: To describe the prevalence and distribution of lower limb overuse injuries in 67 elite New Zealand triathletes.

Study design and subjects: Data were extracted from the High Performance Sport New Zealand athlete database for six years (2007-2012). Frequency of lower limb injuries were analysed by year, injury location and type.

Results: Calf (17%), Achilles tendon (17%), knee (15%) and upper leg (15%) injuries were most common. Muscle was the most commonly affected tissue (33%) followed by tendon (23%). Bony injuries and fascia injuries in the form of iliotibial band friction syndrome (6%) were common.

Discussion: Calf and Achilles tendon overuse injuries for New Zealand elite and development triathletes is consistent with international data.

Conclusions: Achilles tendon and calf injuries are among the most prevalent injuries in New Zealand's high performance triathletes. Given the severity of Achilles tendon injuries, identifying preventative interventions would be beneficial.

Introduction

Injury prevention is a significant factor in sports performance. In the battle for medals and World Championship rankings, keeping athletes injury free aids in maximising training and racing opportunities. However, before injury prevention strategies can be implemented, an understanding of the extent of the problem is essential (7, 24, 81).

Overuse injuries are of concern to triathletes with prevalence reported between 60 and 89% (11, 16, 25, 27, 82). While there is some contradiction in the literature as to which injury type is more prevalent, tendinopathies and muscle strains are the most reported injuries in both amateur and elite triathletes (16, 18, 27, 82). The knee, back and Achilles tendon were reported as the most common body sites of pain causing reduced or lost training for studies of elite and age group triathletes in the United Kingdom (Olympic distance) (17) and Europe (long distance) (5). Of these injuries, Achilles tendon overuse has been reported as the most severe based on number of training days lost (18). Healing time can be up to a year and current treatment protocols are often painful (83, 84). Resolution of Achilles tendon overuse symptoms does not guarantee full recovery of musculotendinous function and reoccurrence of pain and reduced function is common forcing 3-5% of athletes into sporting retirement (85).

Media stories of some of New Zealand's top Olympic distance triathletes (86, 87), and anecdotal reports from within High Performance Sport New Zealand (HPSNZ), suggested that Achilles tendon complaints, calf and shin problems are the most prominent injuries sustained by these individuals. There may be an association between calf muscle tightness and strain and the development of Achilles tendon injuries (88). Achilles tendon injuries are not limited to Olympic distance triathletes, with a number of prominent New Zealand long distance athletes having to take time out from training and racing in recent years (89, 90).

While reports in the media highlight the issue when the country's top ranking triathletes are forced to step down from a race, formal injury surveillance has not been carried out on New Zealand triathletes since the mid 1980's (91). Triathlon races have changed substantially in the last 20 years, particularly Olympic distance elite races, moving from non-drafting to draft legal races with triathlon's introduction to the Olympic Games in 2000. This in turn has contributed to an increased focus on the run as the key discipline from a performance perspective (92), which is also the discipline with the highest risk of injury (8, 16, 92).

Despite an increasing number of international studies on triathlon injuries, there is a paucity of studies describing injuries in New Zealand triathletes and there is limited longitudinal triathlete injury surveillance data. With this in mind the aim of this study was to provide an epidemiological overview of elite triathlete injuries in New Zealand over six years. An investigation of the carded elite athletes in the High Performance Sport New Zealand programme from 2007 to 2012 was conducted.

Methods

Data limitations

Epidemiological studies are dependent on data quality for any analysis to be undertaken (93). Data analysed in this study were from the High Performance Sport New Zealand (HPSNZ) database and were dependent on the athlete or their coach reporting an injury to HPSNZ or being treated for an overuse injury by the lead physiotherapist for the Triathlon NZ High Performance program. The decentralised structure that triathlon has assumed in New Zealand over the past 30 years has likely resulted in some athletes and their data being lost for analysis. Athletes live and train both throughout the country and around the world and therefore may seek treatment from healthcare providers outside of the high performance program. If these providers do not pass on the data, injury occurrences may be lost. The nature of the injury reporting requires that an athlete seek treatment for the injury and therefore the more severe injuries may be over represented. The typical injury definition selected for triathlon studies is "pain or dysfunction resulting in reduced or loss of training for at least one session (or one day)" (16). It is not uncommon for a triathlete to reduce the discipline that causes pain and increase the other disciplines to compensate, without seeking medical advice or treatment (16). Therefore it is likely that a number of minor injuries will have been lost.

Participants

Athletes included in this study were those supported through the Triathlon NZ High Performance programme. Each year athlete selection criteria for the high performance program differed depending on the goals for the year which were primarily focused around the four year Olympic cycle. Criteria included previous race performances as well as time trials in each of the three disciplines. Only very prominent and successful long course athletes were carded and this was halted in 2011 with a focus for the Triathlon NZ High Performance program shifting completely towards Olympic medal count.

Athletes enrolled under the HPSNZ high performance program had access to the medical services provided, including a lead physiotherapist who was responsible for recording all injuries presented by carded athletes. Prior to the formation of HPSNZ in 2011, the same system was provided via the NZ Academy of Sport network, consisting of North and South Island entities with each collecting information which was then collated.

The study period was six years from 2007-2012. During this time 67 athletes passed through the high performance programmes' four tiers: junior development; development; Olympic development; Olympic podium (94). Athletes within the HPSNZ system raced at four different levels: Junior (or Under 19) Sprint distance triathlon (750 m swim, 20 km cycle, 5 km run); Under 23 Olympic distance triathlon (1500 m swim, 40 km cycle, 10 km run); Elite Olympic distance triathlon; and Long course (half ironman up to ironman distance).

Athletes were required to be in the high performance programme for at least six months to be included in the research. Athletes de-carded within the first six months of a year were excluded from that years athlete count. Likewise, if carding occurred in the final six months of a year athletes were excluded from that year's athlete count.

It is important to note that there are a number of New Zealand athletes who race at the elite level, locally and internationally but have not met the selection criteria. These athletes often perform at a similar level to one of the high performance tiers, however are not included in these data.

Ethical consent

All athletes, upon being carded as part of the Triathlon NZ High Performance program, are required to sign an HPSNZ (and previously NZ Academy of Sport) consent to the collection, use and storage of personal information form. This consent allows HPSNZ to use athletes personal information for specific purposes including "Undertake research that will lead to an enhancement of HPSNZ's services" (95). Data were de-identified by HPSNZ and provided to the SPRINZ Clinic for analysis under the university ethics approval # 12/332. Informed consent from the injured participants was not obtained as data were collected from the SPRINZ data base without individual player identification or follow-up.

Data extraction and statistical analyses

Lower limb overuse injuries were the focus given the likely detrimental effects on training and racing. All data collected were entered into a Microsoft Excel spreadsheet and were analysed by injury site and injury type for each year. Injury incidences were reported as a percentage of the triathlete elite population. For overuse injuries that were on-going over multiple years, incidence was recorded once in the first year the injury occurred or the first year of the study. Injuries were analysed by location (foot, ankle, Achilles tendon, calf, shin, knee, upper leg, and hamstring), affected tissue (bone, muscle, tendon, ligament, and nerves), and diagnosis (fracture, strain, tendon injury, and stress reaction).

Results

During the six years, 67 athletes (36 male, 31 female) passed through the Triathlon NZ High Performance program; 63 raced Sprint and/or Olympic distance and four were long course athletes. During this time there were 52 new and on-going lower limb overuse injuries reported to the high performance medical staff by 29 (43%) athletes. The average number of injuries was 1.9 ±1.6 per injured athlete, distributed as 1.5 ±0.7 for males and 2.5 ±2.4 for females. Accounting for injured and non-injured athletes, the average number of injuries per athlete was 0.8 ±1.4, 0.7 ±0.9 for males and 0.9 ±1.9 for females.

Injuries were primarily attributed to running (85%) and were more commonly the result of training (70%) rather than competition (4%). Injury incidence was greater in 2011 compared with the other years.

Table 2.1: Triathlete numbers, and athletes injured, in the Triathlon New Zealand High Performance program from 2007 to 2012

Year	Male	Female	Total	Injured athletes	Injury incidence per 100 athletes
2007	22	13	35	7	20
2008	19	19	38	6	16
2009	21	14	35	12	34
2010	14	11	25	5	20
2011	9	7	16	11	69
2012	10	11	21	10	48
Total	36	31	67	51	

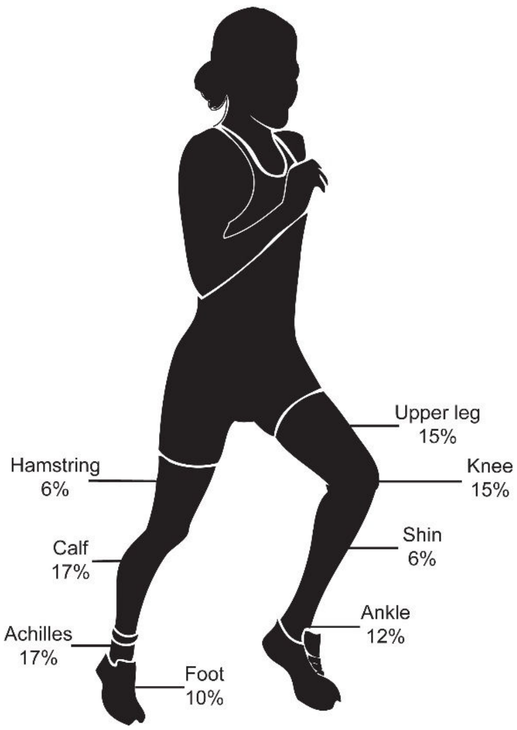

Figure 2.1: Injury frequencies for male and female triathletes in the Triathlon New Zealand High Performance Program from 2007 to 2012

Total reported injuries by injury site

Of the 52 injuries, calf and Achilles tendon injuries were the most prominent followed by knee and upper leg injuries (see Figure 1).

Total reported injuries by type

Of the 52 injuries reported, muscle strains were the most common (33%), followed by tendon related injuries (23%) and fascia injuries (12%) which were most commonly in the form of iliotibial band friction syndrome (6%). Stress fractures (4%), sprains (4%), impingements (2%), nerve (2%) were also reported. Twelve percent of injuries were not adequately classified in the data.

Discussion

During the six year study period 43% of athletes passing through the high performance system reported at least one new or on-going injury. This is a smaller percentage of athletes sustaining overuse injury (or at least reporting overuse injury to the national database) than was reported for the British Senior squad for a five year retrospective study in the 1990's (16). The current data (43%) is within the range 37-91% reported in the literature for triathletes (2-5, 8, 18, 96, 97). The lower number of injuries reported compared to British athletes despite a similar level of competition is likely due in part to the focus on lower limb injuries only. In addition minor injuries that only caused minimal disruption to training may not have been reported to the medical staff. Burns et al. (2) noted that 50% of athletes competing in the 1999 Australian domestic season reported at least one injury in the six month preseason, of which 75% were lower limb injuries. It is also worth noting that the previously acknowledged limitations of injury reporting in this period mean that all statistics should be regarded as a minimum and could potentially be higher.

As reported previously in the literature, knee, calf and Achilles tendon were among the most common injuries in triathletes, however, differences in defining and combining injuries make comparisons difficult. Vleck et al. (18) classified Achilles tendon injuries as the most severe lower limb injuries based on the number of training days lost to the injury. According to Tauton et al. (98) males are at higher risk of developing Achilles tendon injuries than females. While our limited injury numbers did not allow a valid analysis by gender, females appeared to dominate the Achilles tendon injuries.

Tendon and muscle were found to be the most common tissues affected. Similar results were reported in a group of French Olympic and long distance triathletes (27) and long distance European triathletes (5). The Achilles tendon was the most common tendon to cause pain and dysfunction in our sample of triathletes.

Egermann et al. (5) reported that most injuries in triathletes occurred during cycling. However, cycling crashes were included in this data set. Patello-femoral pain is commonly reported in cyclists as well as runners and is a common source of knee pain (98, 99). Iliotibial band friction syndrome is also commonly attributed to cycling (100) (16, 18, 96). In contrast, approximately 65% of overuse injuries were attributed to running by other research, with cycling only accounting for 20-35% (4, 8, 16, 18).

The current data shows a higher proportion of injuries (85%) related to running. The focus on lower limb injuries excludes most swimming related injuries and therefore could cause the running related injuries to be higher. Previous research has typically relied on self-reported injury cause rather than professional diagnosis. It is therefore likely that the reported causative activity is the one the athlete associates the most pain with. Causation in the current data could be the combination of the athlete's pain experience and the reporting physiotherapist's professional experience. The professional insight could account for the higher percentage of running related injuries. In all cases it is important to note the possibilities of cumulative stress from multiple disciplines when interpreting the cause of injuries in triathletes.

Finally all previous data comes from prior to 2000 when incorporation into the Olympic Games altered the nature of the race. A greater focus on the run leg with associated increased emphasis on run training could account for the increase in running related injuries. In the mid 80's approximately 51% of New Zealand triathletes reported injuries, only 20% of which were severe enough to stop training or withdraw from a race (91). Fifty-three percent of the reported injuries were associated with running, 50% with cycling and only 11% with swimming, including injuries attributed to multiple disciplines. While the number of injured athletes (43%) appears smaller for the more recent New Zealand data, this is likely due to only the more severe injuries being recorded. Injuries associated with running are far more common now than in the early years of triathlon. However, the populations also differed in race level, with elite and elite development in the current study compared to all triathletes targeted in 1988.

Injury numbers were greater in the later years investigated. Although the reasons for this are not known definitively, it may be due to an improvement in injury reporting systems coming into a new Olympic cycle. High performance squad numbers decreased from 35-38 in 2007-2009 to 16-25 in 2010-2012. The smaller number of athletes to monitor in the high performance squad in more recent years, combined with improved internal injury surveillance systems, are likely to have improved the accuracy of the information available. It is also worth noting that injury incidence was greatest in 2011, a pre-Olympic year. The increased emphasis on racing in order to qualify during this period could increase the risk of athletes becoming injured. The high importance of run performance in determining the race outcome may also contribute to increasing injury incidences in more recent years. Many triathletes have adopted training similar in intensity and volume to elite distance runners, potentially increasing the risk of running related injuries. Adding training for two other disciplines would add to injury risk by decreasing recovery time.

Conclusions

A snapshot of the prevalence of injuries and their distribution in New Zealand's elite and most promising developing athletes showed that lower leg injuries, particularly Achilles tendon and calf injuries, are problematic. Given the severity of Achilles tendon injuries, development of preventative interventions would be warranted. Injuries were primarily attributed to running, however, crossover between the disciplines is likely.

CHAPTER 3

ACHILLES TENDON INJURY RISK FACTORS ASSOCIATED WITH RUNNING: A SYSTEMATIC REVIEW

This chapter comprises the following paper:

Lorimer, A., Hume, P., *Achilles tendon injury risk factors associated with running*. Sports Medicine, 2014: p. 1-14. Published ahead of print.

Overview

Background: Research into the nature of overuse Achilles tendon injuries is extensive, yet uncertainty remains around how to identify athletes susceptible to Achilles tendon injury.

Aim: To identify the strength of evidence for biomechanical risk factors associated with Achilles tendon injuries.

Research methods: SPORTDiscus, CINAHL, Web of Science and PubMed were searched for Achilles tendon injury risk factors and biomechanical measures which are altered in runners with Achilles tendon injuries, excluding ruptures. Fifteen articles were included in the analysis.

Results: Two variables, high vertical forces and high arch, showed strong evidence for reduced injury risk. High propulsive forces and running on stiffer surfaces may also be protective. Only one biomechanical variable, high braking force, showed clear evidence for increasing Achilles injury risk.

Discussion: Gait retraining to direct the centre of mass further forward to reduce high braking force could be useful in decreasing the risk of Achilles injury. The majority of biomechanical risk factors examined showed unclear results, which is likely due 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 both prior to landing and immediately post ground contact and joint motion throughout stance.

Conclusion: Multiple risk factors have been associated with development of Achilles tendon injuries in running athletes but most effects remain unclear. Advice for athletes recovering from Achilles tendon injuries could include avoiding soft surfaces and reducing the pace of recovery runs. Orthotic intervention could assist athletes with low arches but modification of pronation should be viewed with caution. Strength training and gait retraining could be beneficial for reducing injury risk.

Introduction

Despite many risk factors being identified for Achilles injuries, understanding of the causation of the injury remains unclear. Collation of all the possible risk factors and assessment of the strength of evidence for each is required in order to determine how preventative interventions should be approached.

Lower-limb injuries have been identified as the most common overuse injuries in running athletes (101). Of these, chronic Achilles tendon (from here on referred to as Achilles) injuries (commonly referred to as tendonitis or tendinopathy) are one of the most severe in terms of the amount of training and racing time lost as a result of the injury (18). Tendinopathies occur in two locations of the Achilles – the mid-portion where the cross-sectional area is smallest (102), or where the tendon inserts onto the calcaneus. Collagen fibres from the soleus, medial gastrocnemius and lateral gastrocnemius come together in the mid-portion of the Achilles tendon. Achilles tendon injuries are present in the general population, with a mid-portion incidence rate of 1.85 per 1,000 Dutch GP registered patients (77). A comparison of the cumulative incidence of chronic Achilles injuries in former elite Finnish athletes and age-matched controls before the age of 45 years found the age and occupation adjusted odds ratio (OR) to be 31.2 (95% confidence interval [CI] 13.5-71.8) for middle and long-distance runners (78). Athletes who had experienced Achilles injuries had more ongoing orthopaedic issues later in life (78). Results of treatment for Achilles injuries are variable, often requiring surgical intervention and, in 3-5% of cases, Achilles injuries can be career ending (83-85). It is therefore apparent that the middle- to long-distance running population is at higher risk of Achilles injuries, resulting in health and personal cost, both immediately and in the future.

Running is a highly repetitive movement, involving large forces, applied through the lower limbs approximately 90 times per minute. Joint motion and muscle activity both before and after ground contact determine the impact force vector, stabilise the limb, store energy and apply force to the ground in order to maintain forward motion (103, 104). Upon contact with the ground, forces are transferred up the kinetic chain via the joints, allowing progressive dissipation of the forces via absorption by the bony structures and soft tissue (105). From the foot, forces are transferred via the ankle to the shank structures, particularly the Achilles tendon and calf muscles. As a soft-tissue structure, encountering forces early in the absorption process, the Achilles tendon is subject to high loads, up to six times body weight (47). Biomechanical characteristics of gait are modified in response to the training environment in order to reduce potentially injurious forces to the musculoskeletal system and maintain performance (106-108).

The Achilles is key for efficient human locomotion. Upon foot contact with the ground, the tendon stretches, storing potential energy, which is then returned in the second half of stance, driving force production and contributing over 50% of the positive work done at the ankle during running (75). However, the Achilles cannot and does not work in isolation. It is intrinsically linked to the direct muscle actions of the gastrocnemius and soleus and joint movements of the ankle (109) and foot (110) as well as indirectly by muscle action and joint motion in more proximal locations (111). Therefore, tendon mechanical properties and functions alone are unlikely to explain a complex and multifactorial injury process, such as for Achilles injuries.

The mechanism of Achilles injuries has long been under debate. The main themes apparent in the literature regarding the possible mechanism of Achilles injury are tensile loading (112), shearing (74) or hyperthermia (75, 76). These mechanisms result in 'non-homologous loading' which can lead to tissue degeneration (43). The insertion or enthesis is the site of greatest strain (113), whereas the mid-portion is subject to the greatest stress ex vivo (46, 114). Along the length of the tendon, strain is variable with no identifiable pattern (46). With chronic tendinopathies, it is plausible that localized damage results in scar formation, or an area of weakened tissue. The area of weakness becomes progressively larger when loaded before repair is complete, producing a cycle of progressively weakening and dysfunctional tissue. If loading occurs before completion of the healing process to original strength, then the uneven stress and strain would be enhanced, increasing the risk of further damage (Figure 3.1). Despite extensive research in multiple disciplines, there is still no clear understanding surrounding the causes of Achilles injuries and why some people develop painful tendons. Multiple mechanisms may be responsible for increasing the complexity of the injury process and obscuring results. Understanding which loading patterns contribute to 'non-homologous' loading would provide insight into the causes of Achilles overuse injuries.

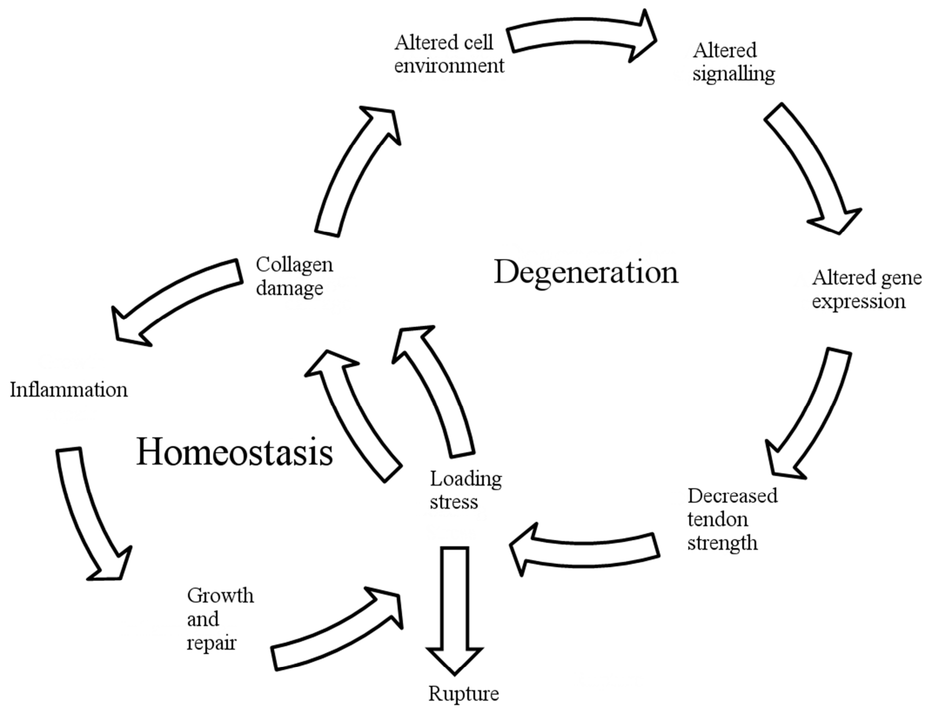

Figure 3.1: Cycle of tendon homeostasis and degeneration

Drawing on the possible mechanisms of injury, a number of factors have been identified that could increase the risk of developing an Achilles injury. Risk factors include increasing age, being male, training error, shoe characteristics, soft surfaces, cold, and pronation (115). Overuse injuries are likely to be multifactorial in nature, resulting from a combination of risk factors rather than one specific issue (116). Prevention of an injury is preferable to treatment. Therefore, causative factors need to be identified in order to predict which individuals are at risk of developing Achilles injuries. An investigation into the extent to which different risk factors are modified in runners with Achilles injuries will highlight areas to focus on for future research into potentially modifiable causative factors. A single measurement that incorporates multiple risk factors and is capable of identifying at-risk athletes would be ideal.

Aim

While there has been extensive research, there is still little understanding surrounding the cause of Achilles injuries. This systematic review aimed to synthesise and determine the strength of the evidence for biomechanical risk factors associated with developing Achilles tendon injuries in running athletes. Identification of factors that are clearly altered in the presence of Achilles injuries will direct research into risk assessment and preventative interventions. Areas where further research is required have been highlighted.

Methods

Literature search methodology

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 (117).

Search parameters and criteria

A search of the literature was conducted for Achilles risk factors and mechanisms. The PubMed, CINAHL, Web of Science and SPORTDiscus databases, to September 2013, were searched for terms linked with Boolean operators (‘AND’, ‘OR’, ‘NOT’): ‘Achilles tendon injury’, ‘tendinopath*’, ‘running’, ‘overuse’, ‘kinematics’, ‘kinetics’, ‘biomechanics’, ‘risk factors’. Papers were selected based on title, then abstract and finally text. Only papers that had runners in the study population, and specifically addressed Achilles tendon injuries within an injury analysis, were included in the tabulated data analysis. Papers were excluded if their content included the following topics: surgery, treatment, diagnosis, rupture, and tendinopathy associated with disease or medication. Case reports, reviews, editorials, letters to the editor and all animal studies were excluded. Studies on Achilles rupture were excluded due to the different mechanism and presentation of injury. Both insertional and mid-portion tendon injuries were included in order to prevent loss of information due to self-reporting of injuries and different injury location analysis.

A total of 2,935 papers were identified, of which 2,009 were duplicates. After selection for inclusion criteria and elimination based on exclusion criteria, 15 papers were left for inclusion into the final review (see Figure 3.2).

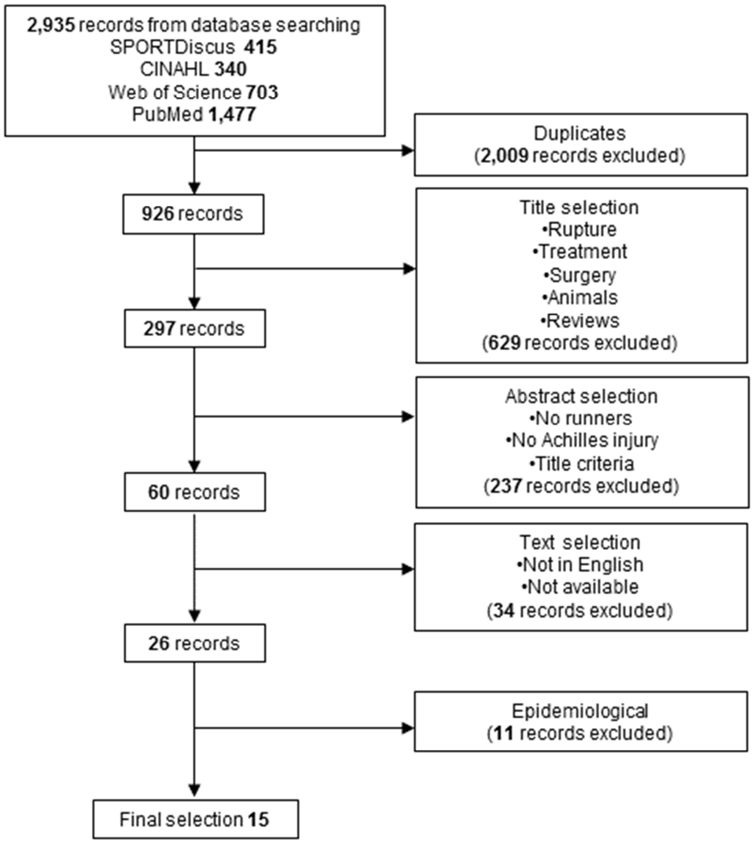

Figure 3.2: Flow of information through the different phases of the systematic review

Assessment of study quality for systematic review and data extraction

Due to the diversity of study types (retrospective cohort with case control, prospective cohort, retrospective questionnaire cohort etc as reported in Table 3.1), a new 8-item study inclusion criteria scale was developed based on the PEDro (118) and Bizzini scales (119) (1 = eligibility criteria were specified; 2 = exclusion criteria described; 3 = each group contained at least 10 participants; 4 = groups were similar at baseline for height, weight, sex, age (no significant difference); 5 = follow-up period or retrospective period were appropriate/cross-sectional studies employed randomisation where appropriate; 6 = outcome measures were appropriate for method and aims; 7 = both effect of injury measurements and variability measurements for at least one key outcome measure were included; 8 = statistical analysis was detailed). 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 the research does not allow blinding and true randomisation. If groups were not similar at baseline for key variables then a study quality point was achieved if group differences were taken into account in the analysis (e.g. weight-normalised measurements). Where randomisation was not possible, such as retrospective analysis or case-control with only one measurement, or a reason for lack of randomisation was given, the study quality point was awarded. Effect of injury required means, ORs or proportions, and required CIs or standard deviations, to meet these criteria. The quality scores based on the paper selection criteria ranged from 4 to 7, shown in round brackets in Table 3.1.

Analysis and interpretation of results

Odds ratios were converted to effect size (ES) by multiplying the natural log OR and confidence limits by $\sqrt{3}/\pi$ (117, 120). Effect sizes with 95% confidence limits were calculated from means and standard deviations. All results are summarised as ESs in Table 3.1. Factors that were assessed in more than one study were averaged and are presented as a forest plot (Figure 3.3). The majority of variables were only addressed in two studies. Where more than two studies were used, the number of studies is given as 'n' in brackets. A negative ES indicates that increasing the variable of interest may be detrimental to an athlete in terms of Achilles tendon injuries, while a positive ES indicates that increasing the variable may be protective. An ES 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 (121).

Results

A number of extrinsic and intrinsic risk factors have been identified for running-related Achilles injuries including, demographic, training, environmental, static alignment, strength, joint motion and ground reaction forces (11, 122-124).

Five risk factors showed clear effects when ESs were averaged across all studies (see Figure 3.3). High peak vertical ground reaction forces (ES 5.71; 95% CI 5.67–5.74) and greater arch height (2.5; 1.97–2.97) had very large effects for reducing Achilles injury risk. Running on stiffer surfaces (1.09; 0.09–2.10) had a moderate protective effect, and peak propulsive force (0.27; 0.267–0.278) had a small protective effect. Only one variable investigated, peak braking force (-1.33; -1.34—1.32), showed a clear, large, increased risk of injury. The effect of all other variables were unclear.

Table 3.1 provides the results of all biomechanical, demographic and training risk factors assessed as individual study ESs with 95% confidence limits.

Table 3.1: Summary of findings for differences between uninjured runners and runners with Achilles tendon injuries

Study	Study design/aim [Quality score]	Subject characteristics	Results (ES ± 95% CI)
Taunton et al. (98)	Retrospective with case control multivariate analysis of physical activity and static alignment as risk factors for common running injuries. [7]	2,002 patients with running related injuries, 96 (56 M, 40 F) with AT, other injuries (1,906) as control.	*From OR:* Male over 35 y -0.57±0.44.
Knobloch et al. (125)	Retrospective questionnaire to determine rates and risk factors for running overuse injuries. [4]	291 (249 M, 41 F) returned questionnaires distributed in a German running newsletter, 159 reported AT injuries.	*From OR:* Training on asphalt 0.42±0.35; Training on sand -1.27±1.22; Primary race = Triathlon 0.42±0.82; = Half marathon 0.38±0.33; = 5 km -0.32±0.31; =1500-3000 m -0.51±0.46; 10+ years' experience -0.26±0.27.
Di Caprio et al. (126)	Prospective cohort with multivariate analysis of training, biometric and static alignment risk factors for foot and lower limb injuries. [7]	166 (86 M, 80 F) competitive and recreational runners from Italy, 40 athletes reported AT injuries.	*From OR:* Flat arch -1.56±1.00; Valgus hindfoot 0.63±0.54; Varus hindfoot 0.08±0.76; Train on track surface -0.91±0.79; *From group means:* Years of activity -0.81±1.02; Days per week training -0.60±0.23; Distance per week (km) -0.86±3.80.
Van Ginckel et al. (127)	Prospective cohort, foot pressure distribution during overground running, risk of developing AT injuries. [7]	129 (19 M, 110 F) novice runners in a 10 week Start-to-Run program, 10 (2 M, 8 F) developed diagnosed AT injuries, 53 (8 M, 45 F) with no injuries.	*From group means:* Age 0.21±2.36; Weight 0.01±3.07; Time to peak force 2.00±0.10; Postereo-anterior displacement of COF at last foot contact 0.95±3.60; Postero-anterior displacement of COF at forefoot pushoff 0.75±2.53; Total postero-anterior displacement of COF 0.95±3.59; Distribution of pressure under all metatarsal heads at forefoot flat 0.93±0.03; Distribution of pressure under all metatarsal heads at foot flat -0.70±0.03

Table 3.1 (cont.): Summary of findings for differences between uninjured runners and runners with Achilles tendon injuries

Study	Study design/aim [Quality score]	Subject characteristics	*Results (ES ± 95% CI)*
Haglund-Akerlind & Eriksson. (128)	Cross-sectional case control to determine differences in strength and ankle motion in runners with a history of AT injuries. [7]	10 male runners with history recurrent AT injuries, 10 male runners with no history of AT complaints. Single leg from each subject analysed (injured and random for controls).	*From groups means:* Age -0.48±3.77; Weight -0.27±3.60; Years trained -0.95±2.28; Races per year -0.08±9.30; Sessions per week -0.55±1.03; Distance per week (km) -0.61±20.02; Hill training -0.13±0.45; Strength training -0.55±0.63; Jump training 0.27±0.46; Ankle ROM – knee extended 1.18±5.34; Ankle ROM – knee flexed 1.19±5.19; Passive ankle DF 1.08±4.70; Concentric force @ 180 deg/s 0.78±8.06; Eccentric force @ 180 deg/s 1.31±14.08.
Reule et al. (129)	Cross-sectional case control to determine relationship between STA and AT disorders. [6]	307 (218 M, 89 F) experienced runners to give 314 STA, 95 (80 M, 15 F) with previous experience of AT disorder, 519 (356 M, 163 F) control STA.	*From groups means:* Age -0.67±1.84; Weight -0.29±1.53; Distance per week (km) -0.62±2.73; STA inclination angle -0.12±1.34; STA deviation angle -0.35±1.82; Male- STA inclination angle -0.19±1.48; STA deviation angle -0.26±2.13; Female – STA inclination angle 0.06±2.53; STA deviation angle -0.24±3.13.
Donoghue et al. (41)	Cross-sectional case control with treadmill running kinematic analysis barefoot and shod. [6]	22 (20 M, 2 F) recreational runners, 11 (10 M, 1 F) runners with low graded AT injury and high level of pronation, controls matched for age, sex, height and weight (not matched for pronation).	*From groups means:* Age 0.70±3.51; Weight 0.62±4.31; *Running barefoot* – Leg ABD @ HS 0.46±1.78; Leg ABD max 1.16±1.64; Leg ABD ROM 0.58±1.88; Calcaneal angle @ HS -0.24±1.39; Calcaneal angle max -0.24±1.38; Calcaneal angle ROM 0.08±0.05; Rearfoot EV @ HS -0.34±1.41; Rearfoot EV max -0.03±1.55; Rearfoot EV ROM 0.38±1.11; Ankle DF @ HS 0.08±2.06; Ankle DF max 0.57±1.95; Ankle DF ROM -0.62±1.52; KF @ HS -0.30±2.66; KF max -0.18±3.77; KF ROM -0.05±2.06; *Running shod* – Leg ABD @ HS 0.29±1.54; Leg ABD max 0.75±1.94; Leg ABD ROM 0.50±2.03; Calcaneal angle @ HS -0.63±2.65; Calcaneal angle max 0.57±1.80; Calcaneal angle ROM -0.52±1.24; Rearfoot EV @ HS 0.60±1.88; Rearfoot EV max -0.48±2.06; Rearfoot EV ROM -0.92±2.30; Ankle DF @ HS -0.08±2.30; Ankle DF max 0.57±1.79; Ankle DF ROM -0.75±1.62; KF @ HS 0.00±2.70; KF max 0.14±3.57; KF ROM -0.27±1.41;

Table 3.1 (cont.): Summary of findings for differences between uninjured runners and runners with Achilles tendon injuries

Study	Study design/aim [Quality score]	Subject characteristics	*Results (ES ± 95% CI)*
Ryan et al. (130)	Cross-sectional case control to identify biomechanical differences that can discriminate between runners with AT injuries and those without for overground, barefoot running. [6]	48 male runners, 27 with mid-portion Achilles tendinopathy, confirmed with US, 21 controls injury free for previous six months.	*From groups means:* Age 0.00±2.30; Weight -0.69±2.96; $TROM_{IR/ER}$ -0.40±0.72; $TVel_{IR}$ 0.02±13.9; $tTVel_{IR}$ 0.40±1.44; TIR 0.50±0.58; tTIR -0.22±2.59; $TVel_{ER}$ -0.06±18.3; $tTVel_{ER}$ -0.59±2.45; Ankle DF ROM 0.00±0.88; Ankle DF 0.00±1.01; tAnkle DF -0.38±0.76; Ankle PF ROM 0.00±1.74; Ankle DF-PF ROM 0.25±2.30; Ankle DFVel 0.62±14.15; tAnkle DFVel -0.25±1.16; Ankle PFVel -0.32±33.05; tAnkle PFVel -0.33±0.87; Ankle EV ROM -0.67±0.87; Ankle INV ROM -0.36±1.62; Ankle EV-INV ROM -0.57±2.03; Ankle EV Vel -0.33±43.3; tAnkle EV Vel -0.14±2.03, Ankle EV max 0.33±1.33; tAnkle EV max -0.22±1.33; Ankle INV Vel -0.54±30.89; tAnkle INV Vel -0.40±0.72.
Williams III et al. (131)	Cross-sectional case control, assessing transverse plane kinematics of the knee and tibia in rearfoot strike runners with AT injuries for overground running. [6]	16 (11 M, 5 F) runners, 8 (6 M, 2 F) with diagnosed, asymptomatic Achilles tendinopathy, controls without history of AT injuries matched for age, height, weight and running mileage.	*From groups means:* Age -0.48±4.70; Weight -0.14±6.70; Years running -0.96±4.52; Distance per week (km) -0.27±11.79; TIR max -0.08±3.23; KIR max 0.97±2.32; TER moment max -1.36±0.19; KER moment max 0.17±0.06; KIR-TIR motion timing -0.06±10.83; KER-TER moment timing 0.08±4.99.
Azevedo et al. (132)	Cross-sectional case control, biomechanical variables associated with AT injuries during overground running in standardised shoes. [7]	42 (32 M, 10 F) experienced runners, 21 (16 M, 5 F) with diagnosed mid-portion Achilles tendinopathy (did not restrict running), controls were injury free for at least 2 years	*From groups means:* Age -0.38±3.09; Weight -0.63±3.67; Stride length 0.22±0.08, stride time 0.00±0.02; stride rate -0.18±1.78; H braking force 0.20±0.02; H propulsive force -0.32±0.01; V Force 1st peak -0.51±0.07; Loading rate of 1st peak -0.19±3.22; V Force 2nd peak 3.76±0.06; TA pre 1.00±1.75; TA post -0.16±1.96; PL pre -0.05±1.26; PL post 0.67±2.77; lat. G pre -0.06±1.56; lat. G post 0.45±3.09; RF pre -0.12±1.76; RF post 1.40±2.78; GM pre 0.10±1.49; GM post 1.05±2.11; Hip angle @ HS -0.23±2.31; Hip angle @ TO -0.12±3.11; Hip ROM -0.26±3.42; Knee angle @ HS -0.53±2.17; Knee angle max 0.09±2.17; Knee ROM 1.16±1.16; Ankle angle @ HS -0.06±2.14; Ankle angle max 0.15±2.67. (pre/post = EMG – integrated activity normalised to gait cycle)

Table 3.1 (cont.): Summary of findings for differences between uninjured runners and runners with Achilles tendon injuries

Study	Study design/aim [Quality score]	Subject characteristics	*Results (ES ± 95% CI)*
Baur et al. (133)	Cross-sectional case control, muscle activity and kinetic variables during barefoot treadmill running with AT injuries. [5]	22 experienced runners, 8 with chronic AT injuries.	*From groups means:* Medial deviation COP -0.04±7.37; Lateral deviation COP (normalized to foot length) BF 0.89±16.17; Lateral deviation COP (normalized to foot length) shod 0.24±16.2; lat. G amp BF 1.27±0.32; lat. G amp shod 0.99±0.32; PL onset (% stride) BF 0.28±9.41; PL onset (% stride) shod -0.11±8.36; Braking impulse (%BW/s) BF -0.60±0.10; Braking impulse (%BW/s) shod -0.47±0.13. (amp = EMG – normalised to mean amplitude and gait cycle)
Baur et al. (134)	Cross-sectional case control, neuromuscular control impairments with AT injuries during treadmill running. [6]	60 (40 M, 20 F) experienced runners, 30 (20 M, 10 F) with diagnosed mid-portion Achilles tendinopathy (did not restrict running), controls were free of musculoskeletal symptoms for 6 months.	*From groups means:* Age -0.46±2.23; Weight -0.43± 3.00; Distance per week (km) -0.17±4.61; TA pre 0.04±0.07; TA post -0.09±0.08; TA TO -0.19±0.15; PL pre 0.08±0.09; PL post 0.54±0.15; PL TO 0.03±0.09; PL TO 0.03±0.09; med. G pre -0.08±0.09; med. G post 0.63±0.13; med. G TO 0.40±0.14. (pre/post = EMG – normalised to mean amplitude and gait cycle)
Wyndow et al. (135)	Cross-sectional case control, neuromotor control of the triceps surae during overground running with Achilles tendinopathy. [6]	34 male runners, 15 with mid-portion tendon symptoms, controls had no lower limb symptoms preventing running for more than one week in past 12 months.	*From groups means:* Age -0.79±2.65; Weight -0.29±3.65; Distance per week (km) -0.19±5.44; *Relative offset timing (ms)* Sol-lat.G 0.90±7.00; Sol-med. G 2.81±1.44; lat. G-med. G -1.10±1.31; *Relative onset timing (ms)* Sol-lat. G 1.23±1.85; Sol-med.G -0.17±2.16; lat. G-med. G -1.71±1.90.

Table 3.1 (cont.): Summary of findings for differences between uninjured runners and runners with Achilles tendon injuries

Study	Study design/aim [Quality score]	Subject characteristics	*Results (ES ± 95% CI)*
McCrory et al. (136)	Cross-sectional case control, investigate the relationship between training, anthropometric and biomechanical variables and AT injuries using isokinetic and shod treadmill running analysis. [6]	89 recreational and competitive runners, 31 with mid-portion AT injuries, control had no history of lower limb injuries that prevented running.	*From groups means:* Age -2.72±0.30; Years running -2.15±0.23; Distance per week (km) -2.12±0.76; Training pace 3.12±0.02, Competition pace -2.64±0.02; Q angle 0.19±0.12; Passive DF ROM 0.41±0.15; DF torque @ 180 deg/s 1.83±0.12; Passive PF ROM 1.82±0.20; PF torque @180 deg/s 2.57±0.36; Arch index 3.37±0.00; Pronation @ 10% -0.11±0.08; Pronation ROM -0.37±0.20; Pronation max -0.76±0.16; tPronation max 1.72±0.37; Pronation velocity max -0.07±6.65; EV @ 10% -0.11±0.08; EV ROM -0.45±0.16; EV max 0.96±0.14; tEV max 1.54±0.43; Peak V force 7.66±0.00; Max propulsive force 0.87±0.00; Max braking force -2.86±0.00; Max medial force 0.11±0.00; Max lateral force -3.34±0.00.
Maquirriain et al. (137)	Cross-sectional internal control, measure difference in leg stiffness between affected and unaffected leg during single leg hopping using contact time and flight time. [6]	51 (40 M, 11 F) athletes of various sports (8 track & field) with AT injuries, comparison between injured and uninjured leg.	*From groups means:* Hop height 0.40±0.76, Hop tc -1.28±24.73; Hop tf -4.87±11.37; Velocity 3.95±23.30; Leg stiffness 0.40±0.76.

ABD abduction, *amp* amplitude, *AT* Achilles tendon, *BF* barefoot, *BW* bodyweight, *CI* confidence interval, *COF* center of force, *COP* center of pressure, *DF* dorsiflexion, *EMG* electromyography, *ER* external rotation, *ES* effect size, *EV* eversion, *F* female, *GM* gluteus medius, *H* horizontal, *HS* heel strike, *INV* inversion, *IR* internal rotation, *K* knee, *KF* knee flexion, *lat. G* lateral gastrocnemius, *M* male, *max* maximum, *med. G* medial gastrocnemius, *OR* odds ratio, *PL* peroneus longus, *PF* plantarflexion, *post* 100 ms after heel strike, *pre* 100 ms before heel strike, *RF* rectus femoris, *ROM* range of motion, *Sol* soleus, *STA* subtalar joint axis, *T* tibia, *t* time, *tc* contact time, *tf* flight time, *TA* tibialis anterior, *TO* toe off, *V* vertical, *Vel* velocity.

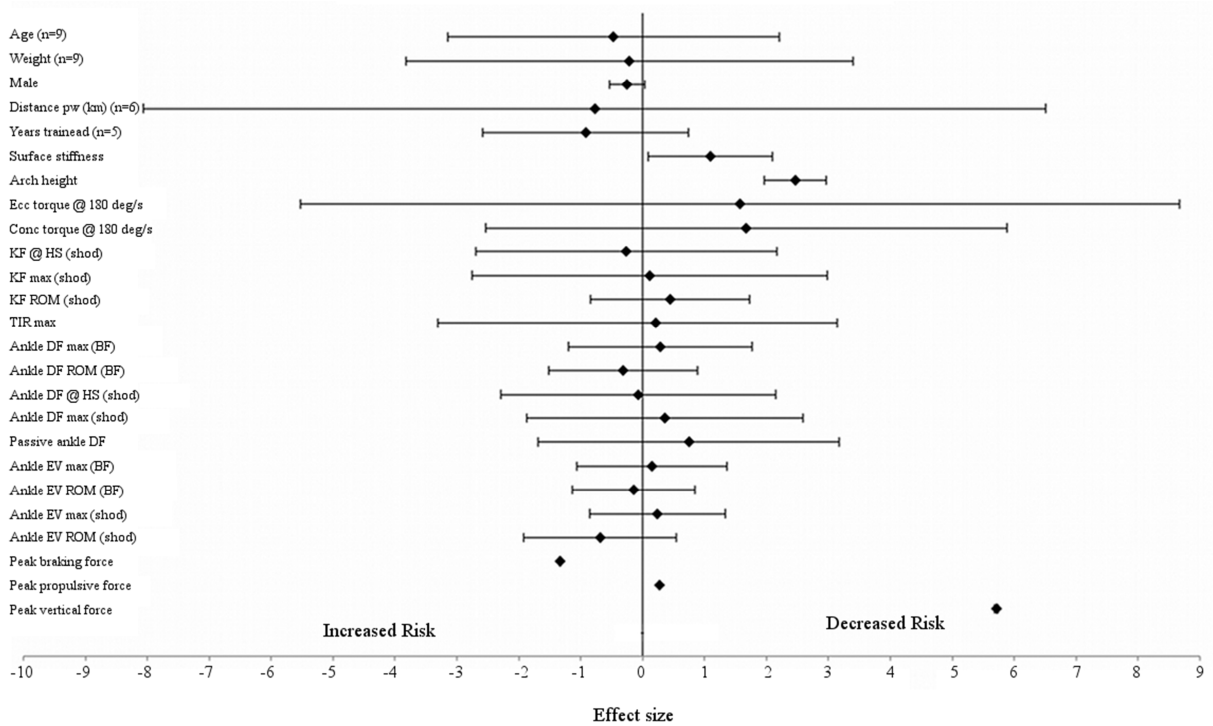

Figure 3.3: Forest plot of effect size (ES) with 95% confidence interval for runners with Achilles tendon injuries compared to uninjured

Number of contributing studies to each variables results is two unless otherwise indicated. BF barefoot, *Conc* concentric, *DF* dorsiflexion, *Ecc* eccentric, *EV* eversion, *HS* heel strike, *KF* knee flexion, *max* maximum, *n* number of contributing studies, *pw* per week, *ROM* range of motion, *TIR* tibial internal rotation. Error bars = 95% confidence intervals.

Age had an unclear effect on tendon health, with some studies showing a beneficial effect and some a harmful effect with increasing age. However, multivariate analysis indicated that males aged over 35 years had a small increase in risk of Achilles tendon injuries (98). Training on soft surfaces such as track or sand had a small and moderate effect of increasing injury risk, respectively (125, 126). Only McCrory et al. (136) showed a clear and very large negative effect for training distance per week and number of years running. A greater training pace (slower velocity) was beneficial, while a greater competition pace had a very large negative effect (136). Of the alignment measures, only a flat arch had a clear and large negative effect (126, 136). A valgus hindfoot had a small, possibly beneficial effect, whereas a varus hindfoot had essentially no effect (126).

Measures of joint angles while running had largely small and unclear effects. Knee range of motion had a possibly moderate positive effect (132) and the maximum tibial external rotation moment had a large and negative effect (131). Pronation variables had either unclear (41, 130) or small effects (136). However, a longer time to peak pronation and peak rearfoot eversion appears to be largely positive (136). Muscle activity had small and unclear effects, however greater triceps surae activity following ground contact and lower antagonist activity could be beneficial (132-134). A more concerted onset of activation of the triceps surae muscles may prevent tendon injuries (135).

Ground reaction forces showed the greatest and clearest effects, with greater vertical forces having a positive effect, while increased braking forces and loading rates negatively impacted the health of tendons (127, 132, 136). Stiffness had a small but unclear positive effect (137).

Discussion

Current information (primarily web-based) targeted at runners and medical practitioners, describe risk factors such as pronation as causative for Achilles injuries. As this review has highlighted, there is, so far, insufficient evidence to suggest that this is the case. Practitioners need to be aware that modifying a single risk factor is unlikely to be sufficient to prevent injury reoccurrence. Research into overuse injuries needs to adopt a new approach looking at the coexistence of multiple risk factors and how they work together to produce injury.

Retrospective and cross-sectional studies of injury can determine risk of injury but with much less strength of evidence than from a prospective cohort design. Differences between control and injured groups could indicate causes of injury but may also be an adaptive response to the injury. It is important to note that without large prospective studies, causation cannot be established. Only two prospective studies assessing Achilles tendon injuries in runners were found (126, 127). Achilles tendon injuries occurred in only 10 of 63 and 40 of 166 subjects over a 10-week and 5 years study period, respectively. Two additional prospective studies looked at Achilles injuries in combat training environments but were omitted from the data analysis due to the different nature of training and footwear (138, 139). The majority of studies have been cross-sectional comparing groups of injured and non-injured runners. Therefore, the majority of evidence is not conclusive in support of risk factors as causative agents of Achilles injuries.

Demographics

Increasing age and being male have long been suggested to increase the risk of Achilles tendon injuries. However, both positive and negative effects of age were observed combined with large standard errors, giving an overall unclear result. This supports the findings of no effect of age or sex on incidences of Achilles tendinopathy in masters track and field athletes (140). The presence of both sexes in the analysis may confound the results. In a multivariate analysis, males aged over 35 years had an increased odds of Achilles injuries (OR 1.67; 1.35–2.06) whereas females aged over 35 years had no change in risk (98). Data were limited to two studies due to cross-sectional studies matching controls to age and sex. However, the present analysis suggests that the effect of sex is small and likely trivial. While increased adiposity has been linked to asymptomatic tendon morphological changes (141), weight appeared to have a very small effect on Achilles injury risk. The large spread of data made the combined results unclear. The results from individual studies showed small and unclear effects.

Training

Training factors are suggested to be associated with risk for all overuse injuries, usually increasing pace or distance too rapidly (125, 126, 142), or excessive hill training (40). Individual analysis showed distance run per week to have a small, unclear, negative effect. Only McCrory et al. (136) showed a clear, very large effect of greater training distance in athletes who developed Achilles injuries. The number of years trained showed a similar trend, indicating that some individuals can withstand the stress of running for longer distances better than others (136). The number of hill training sessions undertaken was not associated with injury (128). Interestingly, a faster training pace but slower race pace was found to be the trend in individuals with Achilles injuries (128). It would appear that athletes who train close to race pace and neglect active recovery with slower training runs are more likely to develop Achilles injuries. Therefore, medical practitioners should advise runners on the importance of slower paces for recovery and endurance runs.

The stiffness of the surface most commonly trained on was clearly related to incidences of Achilles injury (125, 126). More compliant surfaces such as sand and track had a negative effect, whereas stiffer asphalt had a small protective effect (125). Changes in surface stiffness during running and hopping tasks resulted in modification of the leg stiffness in order to maintain the stiffness of the environment-athlete system (106, 107, 143-147). It is possible that the increase in pre- and post-ground contact muscle activity and decreased joint motion required to increase leg stiffness on softer running surfaces add strain to the Achilles tendon, increasing the risk of overload and microdamage. Practitioners should advise athletes returning from injury to limit the time spent running on softer surfaces, such as synthetic track and grass, and should not run on sand if possible.

Static alignment

A larger arch index (136) (i.e. high arches) had a clear, large to very large beneficial effect on reducing injury risk. It has been proposed that athletes with low arches were more likely to sustain soft-tissue injuries, while athletes with high arches had a greater risk of bony injuries (148). A low arch was associated with lower leg stiffness during running, demonstrating a difference in lower limb biomechanics for different foot types (149). In a prospective study in Navy SEAL recruits, both low and high dynamic arch height increased the risk of musculoskeletal injury for barefoot running (138). However, risk ratios for overuse injuries were close to unity for all arch types when shod (138). Good shoe fit for all athletes, regardless of arch height should be emphasised. Practitioners should recommend professional shoe fit and running biomechanics assessment to all athletes to help minimise injury risk. Mean deviation angle was found to be significantly greater in runners with Achilles injuries which could enhance uneven loading through the tendon; however, the effect was small and unclear for injury risk (129).

Strength

The most common conservative approach to treatment of Achilles injuries is eccentric loading; therefore, strength deficiencies have been hypothesised to be involved in the pathomechanics (150-153). Isokinetic analysis at 180°/s showed that injured athletes had reduced eccentric and concentric strength compared with uninjured runners (128, 136). The large variation in torque in one study (128), due to a smaller number of repetitions being used (30 vs. 3), resulted in the combined effect being unclear. A variety of isokinetic velocity profiles resulted in only the eccentric torque reaching significance (p <0.05) when comparing injured and uninjured athletes (128). Eccentric strengthening could be beneficial and loaded eccentric exercise should be maintained once the athlete returns to sport.

Joint and segment motion

The conjecture that excessive or prolonged pronation is contributory to developing Achilles injuries has led to a number of researchers analysing the different aspects of pronation individually, namely rearfoot eversion, abduction and ankle dorsiflexion (41, 130). The intrinsic linkage of the kinetic chain results in transfer of motion from the foot to the lower leg and could contribute to asymmetric loading of the Achilles (110, 113, 154). The coupling of the movement throughout the kinetic chain may also be related to injury risk (155). However, the nature of movement results in increased variation the more focused the measurement becomes. Comparison of lower-leg joint and segment motion during barefoot and shod running generally resulted in small ESs and large CIs making the results unclear. Individual results suggest the peak tibial external rotation moment has a large negative effect, while total knee range of motion, but not maximum knee angle, could have a moderate positive effect (132). A larger tibial external rotation moment in injured runners adds evidence to the potentially protective effect of tibial internal rotation, relieving the load on the tendon (35). Tibial internal rotation is coupled with pronation of the foot during stance, therefore it appears unlikely that pronation increases the risk of Achilles injuries. Pronation range of motions had only a small negative ES; however, there was a moderate negative effect for maximum pronation (136). A greater time to maximum pronation was found during shod running in uninjured runners with similar trends for rearfoot eversion (136). It is therefore possible that the absolute level of pronation does not determine injury risk, but the rate of pronation and the coupling of pronation with tibial transverse motion does. Interestingly, the negative effect of ankle eversion increased when changing from barefoot to shod running, highlighting the significance of the athlete's interaction with the shoe. Practitioners should be wary of modifying the extent of pronation in athletes due to the limited evidence for increased risk of injury with 'excessive' or prolonged pronation.

Forces

High braking forces were the only clearly detrimental variable investigated (see Figure 3.3). Greater braking forces were found in injured athletes and, to a lesser extent, smaller propulsive forces. Increased braking could be the result of a more tentative gait due to the pain of injury. However, in a prospective study of novice runners, a reduced total postero-anterior displacement of the centre of force was significantly associated with the development of Achilles injuries (127). Greater eccentric loading due to a more posteriorly directed centre of force possibly combined with reduced eccentric strength, could rapidly lead to overloading of the muscles and tendons during repeated landings.

In contrast, peak vertical ground reaction force appears to be highly protective (132, 136). Injured athletes are likely to modify landing in response to pain, therefore this effect could be the result rather than cause of injury. However, greater vertical ground reaction force is associated with higher leg stiffness, supporting a hypothesis of lower leg stiffness associated with soft tissue injuries (148, 149). A greater time to peak force appears to be protective indicating a higher rate of loading in injured athletes (127). However, loading rate for the first impact peak showed an insignificant effect (132). Gait retraining could be considered in runners with high braking loads or fast loading rates. Methods could include greater knee flexion motion during the first half of stance and moving the centre of mass forward from the hips throughout the stance phase of the gait cycle.

Muscle activity

The diversity of methods for normalising muscle activity and periods of recording prevented average analysis. The trend, from the individual results, indicate a positive effect for tibialis anterior activation level and a potentially insignificant effect for gastrocnemius activation prior to ground contact (132-134). However, throughout stance the reverse is true. Due to the triceps surae muscles combining at the mid portion of the Achilles tendon, timing of onset and offset of the muscles with respect to each other would contribute to uneven tendon stress and strain (74). A greater disparity between the onset and offset of soleus and gastrocnemius activity appears to have negligible or even large positive effects (135). An asymmetry in timing between the medial and lateral gastrocnemius is likely negatively related to Achilles injuries (135).

Stiffness

Runners with unilateral Achilles injuries had significantly reduced leg stiffness during hopping on the injured side compared with the uninjured leg (137); however, the effect was small and unclear. In individuals (not specifically athletes) with ultrasound-diagnosed Achilles tendinopathy, lower tendon stiffness was observed (156). Ankle joint torsional stiffness during hopping was lower but not significant (p = 0.2) in injured individuals (157). The ES (0.40±0.41) was small but potentially beneficial. Total leg stiffness during hopping was significantly higher in injured athletes, with a potentially large, negative effect (ES -1.73±1.71) (157). Research into stiffness during running and the risk for developing Achilles tendon injuries has not been reported. Modelling has determined that a tendon with lower stiffness has greater hysteresis, increasing intra-tendon temperature (75). High thermal stress could lead to cell death, setting off the cycle of events leading to tendon degeneration (75). However, the relationship between tendon stiffness and running lower-limb stiffness is unclear (158, 159).

Stiffness appears to be associated with a number of potential risk factors for developing Achilles tendon injuries. Stiffness is influenced by muscle activity, joint motion, and tendon and ligament properties. It is possible that the mechanism of injury differs for different individuals, following different routes to achieve the same injury result (160). When a movement pattern is analysed as individual segments and single movements, variability increases. This reduces the likelihood that a clear protective or injurious result will be achieved. Investigating the landing movement holistically may increase the likelihood of identifying injurious movement patterns. A measure that can respond to individual variation yet still predict risk would be ideal. Therefore, as a measure of how the leg responds to the impact of landing, stiffness may provide a method of combining a number of risk factors into a single measure. At this stage, practitioners cannot make any recommendations based on running lower-limb stiffness. Further research is needed in this area.

Conclusions

Large peak braking force was the only variable clearly negative for tendon health. Higher arches, training surface stiffness, peak propulsive force and peak vertical force were found to have a positive effect, potentially reducing the risk of Achilles injuries. All other variables gave unclear results, showing potential to increase and decrease the risk of injury. Potential Achilles tendinopathy risk factors in running athletes include biomechanical, environmental, age, sex, neuromuscular function, and performance level. The high variability of the measurements and the multifactorial nature of overuse injuries obscure individual risk factor analysis. Due to the increased variation of a movement pattern as it is analysed as smaller components, looking at the landing movement holistically may provide greater insight into whether an athlete is at risk of developing Achilles tendon injuries. Further research is required to assess how the various possible risk factors already identified can be incorporated into more holistic measurements. Stiffness could potentially provide one such holistic measure, allowing the identification of at-risk runners prior to the development of injury and progression to preventative interventions.

Given that only high braking force was clearly associated with increased Achilles injury risk in runners, practitioners should consider a combination of multiple risk factors when assessing athletes. Athletes who are recovering from Achilles tendon injuries should be advised to limit the amount of training carried out on soft surfaces, such as running on a synthetic track or grass, and should not run on sand. Orthotic intervention could be considered for athletes with low arches to assist in supporting the structures of the feet and potentially reducing stress and strain to structures further up the lower-limb kinetic chain. Athletes should be advised about the risk associated with running endurance and recovery runs too close to race pace. Improving both eccentric and concentric strength in the athlete utilising functional movement patterns and typical running muscle lengths may assist in rehabilitation and prevention of relapse. Modifying pronation should be viewed with caution as the results are contradictory. Retraining the gait pattern of runners who show large braking forces or rapid loading rates could be beneficial.

CHAPTER 4

STIFFNESS AS A RISK FACTOR FOR ACHILLES TENDON INJURY IN TRIATHLETES AND OTHER RUNNING ATHLETES: SYSTEMATIC REVIEW

This chapter comprises the following paper:

Lorimer, A., Hume, P., *Stiffness as a risk factor for Achilles tendon injury in triathletes and other running athletes: Systematic review*. Under review by Sports Medicine.

Overview

Background: Increased braking force, low arches and lower surface stiffness can increase injury risk while high propulsive and vertical forces are potentially protective. Overuse injuries are multifactorial and likely the result of cumulative small overloads and therefore may not show clear differences between those at risk of injury and those that are not. Utilising a holistic measure that incorporates many of the identified risk factors and looks at movement patterns rather than single joint movements may give better insight into overuse injuries. Lower body stiffness may provide such a measure.

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

Research 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. Stiffness measurement studies using the oscillation technique, quick release or ultrasound were excluded.

Results and discussion: Increased braking force and low surface stiffness were clearly associated with increased risk of Achilles tendon injuries and resulted in 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 results were also investigated with the evidence trending towards an increase in stiffness being detrimental to Achilles tendon health. Variability of methods, models and magnitudes of variable change made summarising the data difficult and further investigation is required.

Conclusion: Large lower body stiffness is potentially associated with increased risk of Achilles tendon injuries although some of the evidence is controversial. Clinicians and coaches may be able to prevent injury or re-injury through encouraging athletes to limit the amount of training on soft surfaces such as sand or track, and limiting the amount of high speed/high intensity work. Variability in lower

leg stiffness should be introduced by increasing the variability of pace, stride rate and stride length in order to distribute the load and allow adequate recovery of tendon micro-injury. Reducing the amount of time spent with large lower body stiffness should be the goal.

Introduction

Achilles tendon injuries are a frustrating injury for athletes due to their slow recovery time and tendency for reoccurrence. Achilles injuries are among the most common injuries in New Zealand (161) and British Olympic distance and British long distance triathletes (16). 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 athletes (15, 18). In club and development athletes, Achilles injuries ranked as number one on the severity scale (18).

The diversity of injury definition and reporting make cross study comparisons difficult (7). The majority of triathlon epidemiology do not specifically look at the Achilles tendon. Achilles injuries are often grouped in with ankle or lower leg injuries – so accurate prevalence information is not known. Ankle, knee and lower leg injuries are the top three overuse injury locations (1, 2, 4, 8) and have been primarily attributed to running (4, 8). Positive correlations between time spent run training and injury risk have been reported (2). Athletes themselves tend to attribute Achilles tendon injuries to the running discipline (18). However, cycling is also considered to contribute to some lower limb injuries (16). Long distance athletes from Great Britain reported no specific origin for Achilles injuries (16).

Of the three triathlon disciplines, cycling and running involve high loads to the lower limbs and therefore the Achilles tendon. Modelling internal loads during stationary cycling estimated Achilles tendon peak forces of 762 N (1.1 BW) (162). Direct measurements using a surgically implanted buckle transducer recorded a peak force of 661 N (163). Workload was the most important variable adjusting tendon loading, whereas cadence had little effect on tendon force (162-164). During running tendon forces have been estimated to reach approximately 6 to 8 bodyweights (BW) at speeds between 3.5 and 5.3 m/s (47, 165). Direct measurement showed tendon forces to reach above 8000 N at a running speed of 5.8 m/s and above 6000 N at the significantly slower 2.0 m/s (166). Ex vivo failure load of the Achilles tendon is between approximately 4500 and 5500 N depending on loading rate (46). While ex vivo results should be compared to the tendon in situ with caution, it appears that Achilles loading during running is very close to the limits of the tendon. Cyclic loading has shown tendon stiffness decreases over time and hysteresis becomes greater which is believed to indicate accumulated damage (114). 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 microscopic damage (individual fibril failure) leads to a cycle of degeneration if sufficient healing does not occur before reloading (43, 167).

Loading during running is significantly greater than during cycling. Muscle activity levels in cycling were similar to walking with lower tendon forces (162, 164, 165). Cycling has therefore been recommended for individuals recovering from Achilles tendon injuries (164). The incidence rate of

Achilles tendon injuries in cyclists is ~9 per 1000 athlete-races (168). Incidence rates in long distance runners are much higher at ~400-800 per 1000 athlete-races (168). Achilles injuries in triathletes are more likely a result of running than cycling, however, the influence of cycling on loading of the Achilles should not be discounted.

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 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 (167). 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 are likely due 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 risk factor analysis highlights the need for an alternative method of assessing injury risk (167). A movement's end result can be achieved by multiple movement patterns (79, 155, 160, 169). It is possible that an injury end point does not arise from a single identifiable factor but from multiple factors working together to cause eventual breakdown of the tissue (79). 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. Lower limb stiffness, from the 'spring-mass model' is considered important in overuse injuries (80). Total leg stiffness during hopping had a potentially large, negative effect size (-1.73±1.71) when comparing injured and uninjured runners (167). Stiffness is also modified by many of the risk factors identified and therefore may provide a useful measure of risk for developing Achilles tendon injuries (167).

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 Figure 4.1) (159, 170). 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. 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 (171-173).

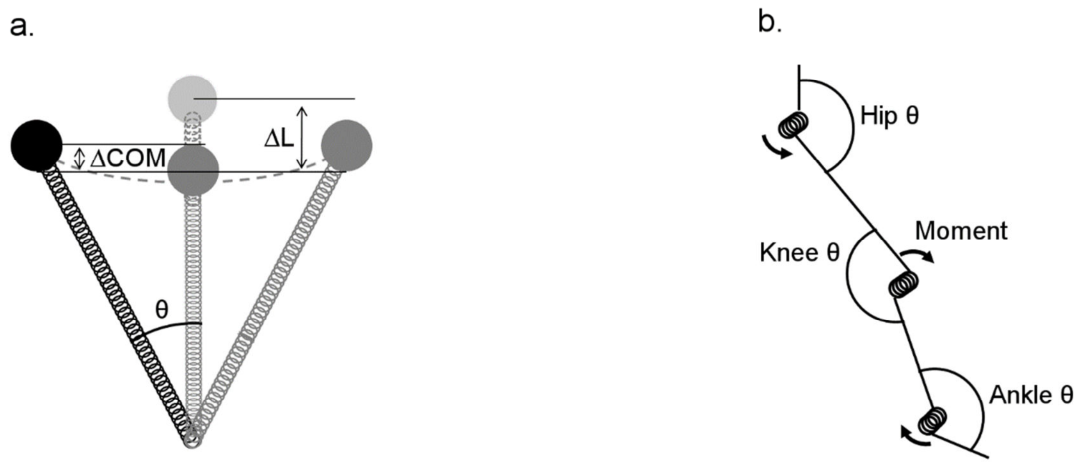

Figure 4.1: Biomechanical stiffness models; a). basic vertical and leg stiffness (159), b). joint stiffness (170)

There are a number of stiffness levels and biomechanical models that can be used to estimate an athlete's 'stiffness' (see Figure 4.1). 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:

$$k_{vertical} = \frac{F_{max}}{\Delta y} \qquad (1)$$

$$k_{leg} = \frac{F_{max}}{\Delta L} \qquad (2)$$

$$k_{joint} = \frac{\Delta M}{\Delta \theta} \qquad (3)$$

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 Δθ is the change in joint angle.

Aim

To determine the extent to which running related risk factors for Achilles tendon injuries modify lower limb stiffness.

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 (117).

Search parameters and criteria

Databases PubMed, SPORTDiscus, CINAHL and Web of Science to November 2013 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; gender. 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 topics: any movement that was not cyclical 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 in English only based on availability. Papers were included that specifically addressed aspects of training or racing encountered by triathletes, such as fatigue and running off the bike. The final search was undertaken in November 2013.

A total of 11,928 papers were identified of which 5,020 were duplicates. After selection for inclusion criteria and elimination based on exclusion criteria, 45 papers were left for inclusion into the final review (see Figure 4.2).

Assessment of study quality for systematic review and data extraction

Due to the diversity of study types (between subject repeated measure, within subject repeated measure and correlation analysis as reported in Tables 4.1 and 4.2), and the known influences on stiffness, a new 9-item study inclusion criteria scale was developed based on the PEDro (118) and Bizzini scales (119) (1= Eligibility criteria were specified (specifically activity level); 2= Exclusion criteria described (specifically injury criteria); 3= Each group contained at least 10 participants; 4= Groups were similar at baseline for height, weight, sex, 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). 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 the research does not allow blinding and true randomisation. Body weight normalisation of results was important when groups were significantly different due 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.

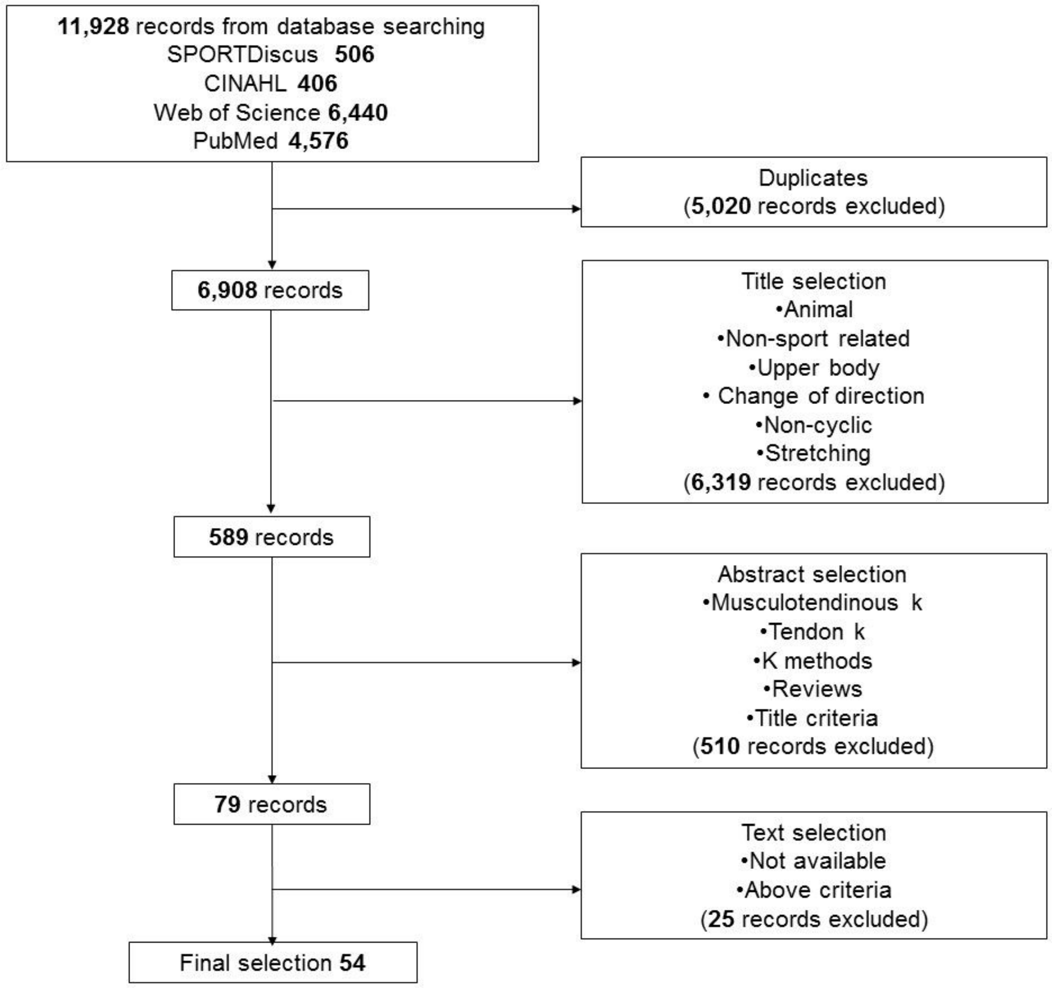

Figure 4.2. Flow of information through the different phases of the systematic review

Analysis and interpretation of results

All changes in stiffness 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 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, due to the lack of complete independence. The lack of exact p-values in the majority of studies prevented the use of alternative methods (174).To maintain consistency, all results were treated with the same method regardless of reporting of p-values. Correlations were converted to effect sizes by $d = \frac{2r}{\sqrt{1-r^2}}$ with confidence intervals calculated using the Fischer's z' transformation prior to effect size conversion (117). Study characteristics and quality scores are reported in Appendix 3. ITU Triathlon World Championship stride rate analysis ranged from 1.4-1.6 Hz, therefore frequency conditions were limited to preferred hopping frequency and 1.5 Hz. Stiffness changes related to the factors identified as clearly increasing or decreasing risk of Achilles tendon injuries, are presented in Table 4.1 while all other risk factors are presented in Table

4.2. Clear results are shaded for clarity. A negative effect size indicates that increasing the variable of interest or the first condition stated decreases the stiffness measure, while a positive effect size indicates that increasing the variable or the first condition stated increases the stiffness measure. 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 (121).

Results

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 (167). Two studies looked at braking force and vertical and leg stiffness (175, 176). Increasing braking force showed a large increase in vertical and leg stiffness when running at preferred pace (175). However, when running at 95% of VO_{2max} there was no clear effect (176)(Table 4.1). Increased propulsive force (F_{ymax}) which demonstrated small protective effects for Achilles injuries (167) was associated with moderate to large increases in both vertical and leg stiffness (175, 176). Three studies reported vertical force (F_{zmax}) and vertical and leg stiffness (175, 177, 178). Running at preferred pace showed clear increases in vertical and leg stiffness with increasing force (175). Increased vertical force with sprinting was associated with an unclear increase in vertical and an increase in leg stiffness (178). Treadmill running at 80% VO_{2peak} however gave an increase in leg stiffness and decrease in vertical stiffness, both of which had unclear effect sizes (177).

As surface stiffness or arch height was increased, risk of Achilles tendon injury was reduced (167). Low arches and low surface stiffness may be harmful to tendon health (167). Three studies looked at vertical stiffness (107, 145, 146), six at leg stiffness (107, 143-146, 179) and one at knee and ankle stiffness with changing surface stiffness (143). There was an increase in vertical stiffness when running across a surface with increasing stiffness at 3.0 m/s (145). 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 (143, 145, 179). All results for knee and ankle stiffness during bipedal hopping were unclear (143). The trend was for decreasing ankle stiffness and increasing knee stiffness as surface stiffness increased. Only one study has looked at arch height and leg and joint stiffness (149). Increasing arch height was associated with an unclear but moderate increase in leg stiffness and a moderate increase in knee stiffness (149).

Table 4.1: Effect of the five clear Achilles tendon risk factors on lower body stiffness measures

Factor	Change	Movement	Vertical		Leg		Knee		Ankle		Ref.
			ES	95% CI	ES	95% CI	ES	95% CI	ES	95% CI	
F_{ymin}	corr.	Run (pref.)	1.57	0.14 : 3.70	1.07	-0.28 : 2.90					(175)
	corr.	Run (95% VO2max)			-0.06	-1.86 : 1.70					(176)
F_{ymax}	corr.	Run (pref.)	1.79	0.30 : 4.06	0.81	-0.52 : 2.50					(175)
	corr.	Run (95% VO2max)			1.91	0.10 : 5.00					(176)
F_{zmax}	corr.	Sprint (max)	0.87	-0.24 : 2.25	1.42	0.24 : 3.04					(178)
	corr.	TM run (80% VO_{2peak})	-0.45	-1.75 : 0.70	0.95	-0.21 : 2.43					(177)
	corr.	Run (pref.)	1.85	0.35 : 4.18	2.98	1.12 : 6.15					(175)
Surface k	21.3 - 533 kN/m	Run (3.0 m/s)	2.27	0.90 : 3.64	-2.88	-4.48 : -1.28					(145)
	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					(146)
	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					(107)
	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	(143)
	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					(144)
	27 - 411 kN/m (expected)	Bi hop (2.2 Hz)			-5.15	-6.88 : -3.42					(179)
	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			(149)

95% CI 95% confidence interval, *bi hop* bipedal hopping, *cont* continuous stiffness surface, *corr* correlation, *ES* effect size, *max* maximum effort, *ref* reference, *TM* treadmill. All clear effects (confidence intervals do not cross zero) are shaded.

Other risk factors (pace variables, age, gender, footwear, muscle activity patterns, intensity and rearfoot angle) did not show clear association with Achilles tendon injury but could be involved in the injury process (167). 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 effect of fatigue was incorporated. Results were variable with only increasing muscle activity and decreasing contact time showing conclusive increased joint stiffness (Table 4.2). The effect of these risk factors on stiffness are given in Table 4.2 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 (175, 178, 180-182). Leg, knee and ankle stiffness showed trivial to small increases with increasing velocity (175, 178, 180, 181, 183). Increasing contact time resulted in decreased vertical (175, 178, 184), leg (175, 178, 185, 186) and ankle stiffness (183, 187, 188). Increasing stride rate resulted in increased vertical (175, 177, 178, 181, 189-191), leg (175, 178, 181, 186, 187, 190-193), knee and ankle stiffness (187, 193). Stride length however was variable, giving increases (175, 178, 181), decreases (176, 178) and no change (175, 181) for both vertical and leg stiffness.

Bipedal hopping at 2.2 Hz and 2.0 Hz resulted in males having moderately larger leg stiffness (194) and moderately smaller leg stiffness (195) compared to females. At 2.5 Hz (195) and preferred hopping frequency (196, 197), the differences were small and both positive and negative. Men had greater leg stiffness than boys (198). Compared to young adults, active elderly had greater knee and ankle stiffness, except when hopping at 100% of maximum hopping height (188). Wearing shoes caused decreased vertical and leg stiffness compared to running barefoot (199). However the reverse was the case for hopping (200). Racing flats caused vertical stiffness to increase slightly compared to standard shoes (201). Increased triceps surae activity was associated with increased leg, knee and ankle stiffness (108, 188, 202). Tibialis anterior activity was positively correlated to decreased ankle stiffness (188). Endurance training gave greater leg and knee stiffness but reduced ankle stiffness compared to untrained individuals (203). Increasing hopping intensity based on body weight resulted in small to moderate increases in leg stiffness but larger increases in knee and ankle stiffness (202).

Fatigue was induced by a large variety of methods and gave approximately equal numbers of increased (175, 176, 182, 204-210), decreased (175-178, 181, 182, 204, 211, 212) and unchanged (175, 176, 197, 206-213) stiffness for both vertical and leg stiffness. Transitioning from cycling to running resulted in small increases in vertical and leg stiffness compared to running alone (214).

Table 4.2: Effect of Achilles tendon injury risk factors on lower body stiffness measures

Factor	Change	Movement	Vertical		Leg		Knee		Ankle		Ref.
			ES	95% CI	ES	95% CI	ES	95% CI	ES	95% CI	
Velocity	corr.	Sprint (max)	0.80	-0.31 : 2.15	0.63	-0.47 : 1.92					(178)
	corr.	Sprint (max)	1.84	-0.11 : 5.29	0.18	-1.74 : 2.25					(181)
	corr. 100m	Sprint	1.28	-0.55 : 4.17							(182)
	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	(183)
	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	
	corr.	Run (pref.)	1.73	0.26 : 3.97	0.15	-1.23 : 1.58					(175)
	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	(180)
	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					(215)
Contact time	corr.	Sprint (max)	-0.80	-2.15 : 0.31	-1.06	-2.52 : 0.07					(178)
	corr.	Run (pref.)	-1.79	-4.06 : -0.30	-1.70	-3.92 : -0.24					(175)
	short - pref.	Run (3.3 m/s)			-2.49	-5.37 : 0.39					(186)
	pref. - long				-3.44	-5.72 : -1.17					
	short - pref.	Bi hop (pref.)			-1.14	-9.73 : 7.44					(185)
	Elderly corr.	Bi hop							-1.54	-2.80 : -0.57	(188)
	70% max corr.	Sprint							-2.76	-6.32 : -0.79	
	100% max corr.								-4.69	-10.18 : -1.91	

Table 4.2 (cont.): Effect of Achilles tendon injury risk factors on lower body stiffness measures

Factor	Change	Movement	Vertical		Leg		Knee		Ankle		Ref.
			ES	95% CI	ES	95% CI	ES	95% CI	ES	95% CI	
SR/Hz	corr.	Sprint (max)	2.08	0.74 : 4.03	0.90	-0.22 : 2.29					(178)
	corr.	Sprint (max)	1.67	-0.23 : 4.94	0.29	-1.60 : 2.42					(181)
	corr.	TM run (80% VO_{2peak})	3.23	1.49 : 6.02							(177)
	corr.	Run (pref.)	2.01	0.47 : 4.44	0.24	-1.11 : 1.71					(175)
	-8% - pref.	Run (78% VO_{2max})	0.95	-2.22 : 4.12	0.55	0.46 : 0.64					(206)
	pref. - +8%		1.28	-2.06 : 4.61	2.43	2.38 : 2.48					
	-26% - pref.	TM run (2.5 m/s)	8.85	5.62 : 12.09	3.09	0.10 : 6.07					(190)
	pref. - +30%		5.69	-0.78 : 12.16	2.53	-0.70 : 5.76					
	-30% - pref.	Run (3.3 m/s)			0.44	-2.30 : 3.18					(186)
	pref. - +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	(187)
	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	(193)
	1.5 - 2.2 Hz (D)	Uni hop			2.43	2.38 : 2.48					(192)
	1.5 - 2.2 Hz (ND)				1.75	1.71 : 1.79					
	-20% - pref.	Uni hop	0.90	-5.48 : 7.28							(189)
	pref -. +20%		1.23	-5.45 : 7.90							
Stride length	corr.	Sprint (max)	-0.61	-1.89 : 0.49	-0.56	-1.83 : 0.54					(178)
	corr.	Sprint (max)	0.59	-1.24 : 2.90	0.00	-1.99 : 1.98					(181)
	corr.	Run (95% VO_{2max})	-0.39	-2.33 : 1.29							(176)
	corr.	Run (pref.)	0.75	-0.58 : 2.41	-0.07	-1.49 : 1.31					(175)

Table 4.2 (cont.): Effect of Achilles tendon injury risk factors on lower body stiffness measures

Factor	Change	Movement	Vertical		Leg		Knee		Ankle		Ref.
			ES	95% CI	ES	95% CI	ES	95% CI	ES	95% CI	
Age	men - boys	Bi hop (1.5 Hz)			-0.79	-7.03 : 5.45					(198)
	Young - elderly (50% max)	Bi hop					0.19	-2.38 : 2.75	0.34	-0.95 : 1.62	(188)
	Young - elderly (75% max)						0.64	-3.60 : 4.87	0.00	-1.53 : 1.53	
	Young - elderly (100% max)						-0.06	-4.24 : 4.11	-1.51	-2.96 : -0.06	
Gender	female - male	Bi hop (2.0 Hz)			-0.72	-0.79 : -0.65					(195)
	female - male	Bi hop (2.2 Hz)			0.68	0.57 : 0.79					(194)
	female - male	Bi hop (2.5 Hz)			-0.15	-0.28 : -0.02					(195)
	female - male	Bi hop (pref.)			0.23	0.10 : 0.36					(216)
	female - male	Bi hop (pref.)			-0.06	-0.23 : 0.11					(197)
	female - male	Bi hop (pref.)			0.36	0.27 : 0.44					(196)
Muscle activity	med. G preact. corr.	Run (pref.)			0.67	-0.98 : 2.76			1.15	-0.51 : 3.58	(108)
	VL onset (arch height) corr.	Run (3.4 m/s)			-0.65	-1.77 : 0.31					(149)
	Sol preact. corr.	Bi hop			0.90	0.19 : 1.71			1.06	0.34 : 1.92	(202)
	lat. G preact. corr.				1.09	0.37 : 1.95			0.70	0.00 : 1.48	
	med. G preact. corr.						1.06	0.34 : 1.92			
	Eld. Sol (BR/PR ratio) corr.	Bi hop							1.67	0.67 : 2.97	(188)
	Eld. med. G (BR/PR ratio) corr.								2.14	1.04 : 3.62	
	Eld. lat. G (BR/PR ratio) corr.								2.41	1.26 : 4.02	
	Eld. TA (BR/PR ratio) corr.								-1.71	-3.03 : -0.71	
	Eld. max TA/Sol coact. corr.								-1.09	-2.20 : -0.19	

Table 4.2 (cont.): Effect of Achilles tendon injury risk factors on lower body stiffness measures

Factor	Change	Movement	Vertical		Leg		Knee		Ankle		Ref.
			ES	95% CI	ES	95% CI	ES	95% CI	ES	95% CI	
Footwear	Barefoot - 350g shoe	TM run (3.6 m/s)	-0.69	-4.06 : 2.68	-0.68	-2.13 : 0.77					(199)
	Shoe - racing flat (F)	Run	0.22	-30.39 : 30.82							(201)
	Shoe - racing flat (M)		0.90	-45.45 : 47.25							
	Barefoot - shoe	Hop (2.2 Hz)			4.00	3.30 : 4.69					(200)
Training status	Untrained - endurance	Bi hop			1.64	1.52 : 1.75	1.63	-5.66 : 8.92	-4.06	-5.90 : -2.22	(203)
RFA	run corr.	Run (3.4-4.2 m/s)			-1.06	-1.98 : -0.29					(217)
	static corr.				-0.93	-1.81 : -0.17					
	closed - opened				-1.13	-3.00 : 0.74					
Intensity	3 BW - 4 BW	Bi hop			0.08	-8.43 : 8.60	1.96	-2.46 : 6.38	1.00	-0.63 : 2.63	(202)
	3 BW - 6 BW				0.87	-6.57 : 8.32	7.07	3.42 : 10.71	2.33	1.11 : 3.56	
Transition	CR - 5% T2	Run (LT)	0.37	-3.58 : 4.32	0.59	-1.28 : 2.46					(214)
	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					(178)
	25m - 375 m	Sprint (max)	-3.26	-15.53 : 9.01	-1.88	-5.68 : 1.92					(181)
	sprint 1 - sprint 2	Sprint	-0.71	-9.61 : 8.18	-0.28	-5.71 : 5.15					(204)
	sprint 1 - sprint 4		-0.39	-8.06 : 7.29	1.13	-3.18 : 5.44					
	1st - 2nd 100m	Sprint	-1.11	-14.43 : 12.21	-0.62	-5.20 : 3.96					(182)
	1st - 4th 100m		-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					(212)
	10 - 100%	Run (95% VO_{2max})	0.09	-2.51 : 0.79	-0.86	-2.51 : 0.79					(176)

Table 4.2 (cont.): Effect of Achilles tendon injury risk factors on lower body stiffness measures

Factor	Change	Movement	Vertical		Leg		Knee		Ankle		Ref.
			ES	95% CI	ES	95% CI	ES	95% CI	ES	95% CI	
Fatigue	pre - post	TM run (80% VO_{2peak})	-0.27	-2.62 : 2.09	-0.26	-1.16 : 0.64					(177)
	pre - post	Run (78% VO_{2max})	-0.17	-4.13 : 3.79	-0.10	-1.61 : 1.41					(206)
	pre - post	Run (70% VO_{2max})	1.30	0.94 : 1.66	0.42	-0.01 : 0.85					(207)
	pre - post + 7 min max		2.82	2.54 : 3.11	0.28	-0.03 : 0.59					
	0 - 2 h	TM run (2.8 m/s)	0.01	-5.60 : 5.63	0.03	-3.69 : 3.75					(209)
	0 - 4 h		0.31	-5.01 : 5.63	0.20	-3.31 : 3.72					
	0 - 24 h		0.58	-4.45 : 5.62	0.42	-2.70 : 3.54					
	Pre - post run sprints	Run (2.8 m/s)	0.24	-4.49 : 4.97	0.17	-4.32 : 4.66					(210)
	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					(205)
	Pre - 3h post	Run (3.3 m/s)	0.52	-1.49 : 2.54	-0.33	-1.24 : 0.57					(208)
	Pre - post	Run (3.6 m/s)	0.01	-6.48 : 6.50	0.01	-2.84 : 2.86					(213)
	1st lap - 4th lap	Run (race)	-0.70	-2.12 : 0.72	-0.34	-1.33 : 0.65					(211)
	1st lap - Finish chute		-0.09	-1.71 : 1.54	-0.12	-1.19 : 0.95					
	200m - 1000m	Run (pref.)	0.31	-0.11 : 0.73	0.52	0.11 : 0.93					(175)
	200m - 2000m		-1.73	-2.11 : -1.35	-0.03	-0.42 : 0.35					
	200m - 5000m		-1.36	-2.08 : -0.65	-0.06	-0.49 : 0.37					
	pre-post squats (M)	Bi hop (pref.)	0.24	0.08 : 0.40	0.18	-17.43 : 17.78					(197)
	pre-post squats (F)		0.16	-6.78 : 6.97	0.18	-11.28 : 11.65					

95% CI 95% confidence interval, *bi hop* bipedal hopping, *BR* braking, *BW* body weight, *coact* coactivation, *corr* correlation, *CR* control run, *D* dominant kicking leg, *Eld* elderly, *ES* effect size, *F* female, *lat. G* lateral gastrocnemius, *LT* lactate threshold, *M* male, *med. G* medial gastrocnemius, *max* maximum effort, *ND* non-dominant kicking leg, *post* post run, *PR* propulsive, *preact* preactivation, *pref* preferred, *pre* before run, *ref* reference, *Sol* soleus, *T2* transition run, *TA* tibialis anterior, *TM* treadmill, *uni hop* unipedal hopping, *VL* vastus lateralis. All clear effects (confidence intervals do not cross zero) are shaded.

Discussion

Summarising the variables that alter stiffness is a difficult task due to 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 complexity 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 due to each study using different parameters of change to the variable of interest.

High braking force was shown to have a clear detrimental effect on Achilles tendon health (167). Increasing surface stiffness, arch height and propulsive and vertical forces were protective (167). 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 lower surface stiffness caused increased leg and ankle stiffness. The greater the change in surface stiffness the more distinct the change in lower limb 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 arch height is potentially protective for 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.

Both protective and injurious factors appear in general to cause increases in stiffness variables. However, many other risk factors have been identified as potentially related to Achilles injury risk (167). Overuse injuries are characterised by progressive onset suggesting that the injury is the result of accumulation of damage from low levels of overload. 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 were also considered.

Pace is a commonly cited risk factor (23) for overuse injuries in general. Faster running pace, or increasing pace too rapidly, are both thought to be associated with injury (23, 126, 184, 218). Vertical stiffness increased with increasing velocity. Decreased contact time and increased stride rate (which are inherently related to velocity) caused varying magnitudes of vertical stiffness increases. Increasing stride length gave 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. (180) looked at changing overground running velocity using the original McMahon and Cheng model (Figure 4.1, a) (159) 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 (180). Decreasing contact time and increasing stride rate gave small to very large increases in leg stiffness, while increasing stride length tended to have little impact on leg stiffness. In the McMahon and Cheng model (Figure 4.1, equations 1 and 2) the difference between vertical and leg stiffness resulted from the addition of horizontal motion. Centre of mass trajectory is unlikely to follow a perfect curve therefore direct measurement is more likely to pick up 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. The distance from the COP to the COM can effect the trajectory of the COM. Therefore, changes in stiffness due to altered stride length are 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 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 (180, 183). Increases in running speed gave 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 stride 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. 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 (219). 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 to altering contact time or stride rate. Combinations of increased stride rate, decreased contact time, increased stride length, increased propulsive force and increased flight time can be utilised to produce the same end running speed.

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. 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 for the Achilles tendon. Muscles and tendons work together to dissipate energy during landing (29). Tendons protect the muscle during landing by allowing slower eccentric actions. However, in order for the tendon to lengthen under load, simultaneous contraction of the muscle is required (29).

The results distinctly showed an increase in knee, ankle and leg stiffness with increasing triceps surae muscle activity. Greater braking/propulsive activity ratio for all three triceps surae muscles resulted in increased stiffness. Increasing muscle force increases the stretch of the tendon (29), 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 (132-135). 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.

Males are reported to be more at risk of Achilles injury than females when over the age of 35 years (98). The effect of gender on stiffness has only been assessed in hopping studies. Both higher and lower stiffness was observed in males when frequency was controlled (194, 195), however there were only trivial to small differences between the genders when allowed to adopt an individual hopping frequency (196, 197, 216). It is possible that during running there would be little difference between genders, when utilising individual 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 hoping height however, knee stiffness was similar while ankle stiffness was lower in the elderly. This effect is probably due to differences in muscle strength and tendon mechanical properties which may decrease with age (220) and compensatory movement patterns developed by active elderly.

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) 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 (221). It was observed that runners adopted a midfoot strike pattern when barefoot which resulted in greater ankle stiffness but allowed reduced impact loading (221). The foot strike pattern rather than the shoe characteristics may be more important in modifying stiffness.

Training distance is another common overuse injury risk factor, which was unclear for Achilles tendon injuries (167). Training distance effect on stiffness has not been measured, but leg and knee stiffness are greater in endurance trained athletes compared to 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.

Pronation may or may not be associated with Achilles tendon injuries with the results varying depending on what part of the movement was investigated (167). The rate of pronation and coupling with tibial rotation may be associated with injury but the evidence is limited (167). Pronation, measured as rear to forefoot angle (RFA) was shown to be associated with stiffness during running for both static and dynamic measurements. Increasing the RFA (pronation) resulted in decreased leg stiffness. Reducing normal pronation increases impact loading (222), therefore increased pronation is likely a protective adaptation. Proprioceptive feedback is important in tuning muscle control and movement patterns in order to achieve the desired task (223). 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.

In triathlon, not only are the straight 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 (224). This period of transition between the two disciplines is believed to increase injury risk. Running economy (224-227) is reduced in triathletes following cycling compared to isolated running. Kinematic changes have been reported following cycling (225, 228). Others have reported no changes in kinematics but altered muscle activity in some athletes (229-231). Proprioceptive feedback adaptations for postural control persist for a short period following cessation of running or cycling activity in triathletes (232). Loss of proprioceptive feedback has been shown to effect interjoint coordination (233). 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 (178, 182, 204), while sustained running at more aerobic intensities (i.e. <75% VO_{2max}) caused increased stiffness depending on the intensity and the time (207-209, 213). 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 (210).

The effect of transitioning from cycling to running has only been directly measured in one study (214). Small, unclear increases in leg and vertical stiffness were observed following cycling when running at lactate threshold. Changes in stiffness were largest immediately following cycling and decreased as the run progressed. During an ITU Championship race, stiffness decreased throughout the run but athletes were able to increase stiffness for the sprint down the finish chute (211). The use of continuous drafting compared to alternative drafting and non-drafting resulted in reduced stride length and increased stride rate (92). Drafting reduces the energy cost of cycling (234). Therefore, gait changes following cycling are more likely the result of muscular fatigue rather than coordination.

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 (80). 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. 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.

Conclusions

Combining the results in order to give an overview of different Achilles tendon injury risk factors on stiffness was made difficult by the diversity of methods, models and magnitude of variable changes utilised. 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 investigation into the use of stiffness as an indicator of Achilles tendon injury is warranted.

Reducing Achilles injury or reinjury risk should be approached with advice against large amounts of high intensity or speed work and running on soft surfaces. Athletes should maintain a high level of variability in training including varying the way in which running pace is increased and utilising a high range of paces. Reducing the amount of time an athlete spends loading the Achilles tendon with high lower body stiffness should be the goal for injury prevention.

CHAPTER 5

COMPARISON OF METHODS FOR QUANTIFYING STIFFNESS AND THEIR RELIABILITY IN TRIATHLETES

This chapter comprises the following paper:

Lorimer, A., Keogh, J.W., Hume, P., *Comparison of methods for quantifying stiffness and their reliability in triathletes***.** Under review by International Biomechanics.

Overview

Lower body stiffness has been implicated in both performance and injury in running athletes. There are a variety of different methods, calculations and stiffness types which can be utilized to analyse the stiffness of an athlete. Vertical, leg and joint stiffness are different levels of measuring how the individual interacts with the environment upon landing. Moving from vertical to joint stiffness provides more specific information regarding the mechanics and tissues involved in the movement task. A comparison of common biomechanical stiffness calculations (dynamic, time, true leg and joint) and stiffness levels and their reliability would enable decisions on which calculations to use for screening stiffness of athletes. Vertical, leg and joint stiffness were estimated in 12 healthy male competitive triathletes on two occasions using both running and hopping tasks. Inter-day reliability was good for vertical (ICC=0.85) and leg (ICC=0.98) stiffness using the time method. Joint stiffness reliability tended to be poor when assessed individually; however reliability was improved when taken as the sum of the hip, knee and ankle (ICC=0.86). The dynamic and time methods of calculating leg stiffness had better reliability than the "true" method. The time and dynamic methods had the best correlation with the different combinations of joint stiffness, therefore should be considered for biomechanical screening of triathletes.

Introduction

Running as a bouncing gait has been successfully modelled using the 'spring-mass model', a point mass balanced on a massless, compressible spring (159, 170). Lower body stiffness, a variable representing the compressibility of the 'leg spring', has been implicated in both performance (235-237) and injury (80, 238) in running athletes.

From a review of the literature, it appears that many Achilles tendon injury risk factors related to the running section of triathlon may also be associated with altered stiffness (167). Stiffness during running is an individual variable determined by muscle activity, joint angles at contact and subsequent joint rotation velocities. These can all be modified around an athlete's base level in response to stride-to-stride variations in the task (i.e. velocity, contact time, prior activity) or the environment (i.e. surface compliance, stepping up/down or shoe characteristics). Determining an athlete's base level and how they respond and modify stiffness in response to different stimuli could be a useful means of analysing the risk of developing Achilles tendon injuries.

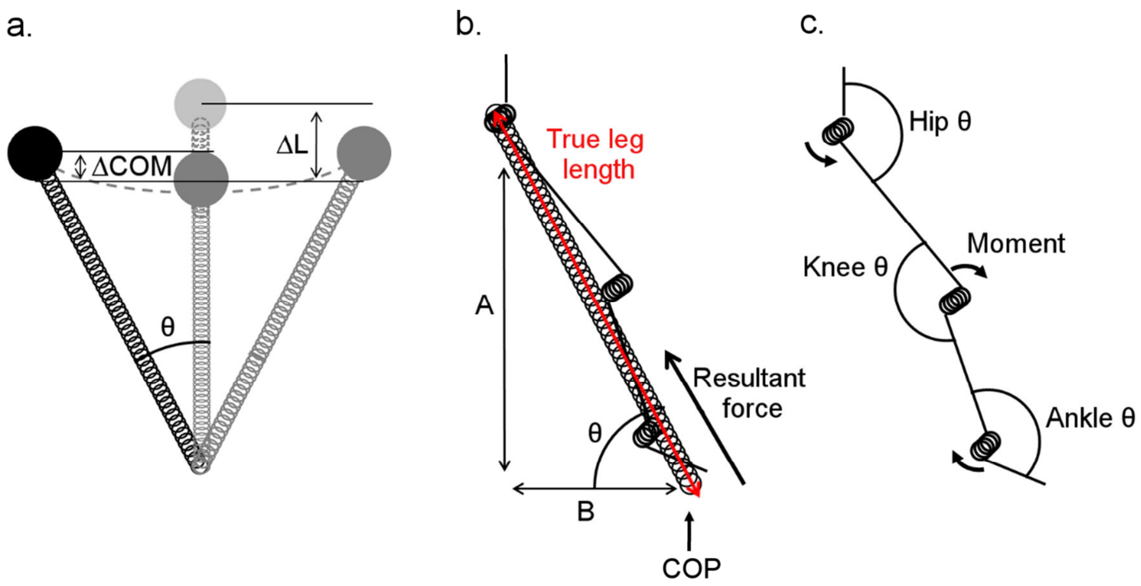

Figure 5.1: Biomechanical stiffness models

a). McMahon and Cheng's (159) spring-mass model for vertical and leg stiffness (159); b). Coleman et al. (239) true leg stiffness model; c). Joint stiffness model (170, 240).

There are a number of stiffness levels and biomechanical models that can be used to estimate an athlete's 'stiffness' (see Figure 5.1). 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 (137, 143, 176, 177, 183, 193, 206, 239-242). Table 5.1 outlines commonly reported stiffness calculations and the key variables required.

Table 5.1: Biomechanical stiffness model calculations, variables and equipment

Stiffness calculation	Terms list	Key variables
Vertical stiffness		
$k_{vert/dynamic} = \frac{F_{max}}{\Delta y}$	F_{max} = peak vertical force, Δy = centre of mass displacement from double integration F_{max}	Vertical force (159)
$k_{vert/time} = \frac{F_{max}}{\Delta y}$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta y = -\frac{F_{max}}{m}\frac{t_c^2}{\pi^2}+g\frac{t_c^2}{8}$	m = subject mass, t_c = contact time, t_f = flight time, g = acceleration due to gravity	Contact time (video or contact mat) (243)
Leg stiffness		
$k_{leg/dynamic} = \frac{F_{max}}{\Delta L}$ $\Delta L = \Delta y + L_0(1-cos\theta)$ $\theta = sin^{-1}\left(\frac{vt_c}{2L_0}\right)$	F_{max} = peak vertical force, ΔL = change in leg length, Δy = centre of mass displacement from double integration of force, L_0 = trochanterian height, θ = angle of leg swing, *v* = horizontal velocity, t_c = contact time	Vertical force Horizontal velocity Standing leg length (159, 243)
$k_{leg/time} = \frac{F_{max}}{\Delta L}$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta y = -\frac{F_{max}}{m}\frac{t_c^2}{\pi^2}+g\frac{t_c^2}{8}$ $\Delta L = L_0 - \sqrt{L_0^2-\left(\frac{vt_c}{2}\right)^2} + \Delta y$	F_{max} = peak vertical force, ΔL = change in leg length, Δy = centre of mass displacement, L_0 = trochanterian height, m = subject mass, t_c = contact time, t_f = flight time, g = acceleration due to gravity, *v* = horizontal velocity	Contact time Horizontal velocity Standing leg length (243)
$k_{leg/true} = \frac{maxF_{leg}}{\Delta L_{true}}$ $F_{leg=cos(\theta_{leg})F_R}$ $F_R = \sqrt{(F_v^2+F_H^2)}$ $\theta_{leg} = (90-\theta_{true})-\theta_R$ $\theta_R = cos^{-1}\left(\frac{F_v}{F_R}\right)$ $\theta_{true} = tan^{-1}\left(\frac{A}{B}\right)$	$maxF_{leg}$ = maximal force directed in line of the leg, ΔL_{true} = true change in leg length, θ_{leg} = angle of leg, F_R = resultant force, F_V = vertical force, F_H = horizontal force, θ_{true} = angle between the calculated L_{true} and horizontal axis, θ_R = angle of the resultant force, A = vertical distance from hip marker to ground, B = horizontal distance from hip marker to centre of pressure	Horizontal force Vertical force High speed video Hip marker Centre of pressure (239)
Joint stiffness		
$k_{joint} = \frac{\Delta M}{\Delta\theta}$	ΔM = change in joint moment, Δθ = change in joint angle	Three dimensional force Lower body video for inverse dynamics calculation (240, 244)

Stiffness can be considered as a multilevel measurement with each level contributing more detailed information about the running movement (160). The body's response to the impact of landing during running is measured as vertical stiffness based on the displacement of the body's centre of mass. Centre of mass displacement is achieved through compression of the 'leg spring' and is influenced by landing geometry and horizontal velocity (108, 245-247). Compression of the 'leg spring' occurs via rotation of the hip, knee and ankle joints, the rate and extent of which is controlled by the surrounding muscles, ligaments and tendons working against the externally applied force (143, 159, 248). Stiffness is regulated both centrally and via reflex responses involving a 'top down, bottom up, top down' pattern (103, 145, 179, 249-251). Both the ankle (240) and knee (252) have been reported as being the joint which primarily controls leg stiffness. When assessing the effect of increasing velocity on leg stiffness, ankle stiffness was reported to remain constant while knee stiffness increased (180). As part of the kinetic chain instrumental in determining the angle of attack, the role of the hip in modifying leg stiffness should not be discounted.

The reliability of vertical (242, 253, 254) and leg (242, 243, 253) stiffness measures have been established. However, joint stiffness (242) has been reported to have poor reliability for hopping tasks and over-ground running. To add complexity to this issue, several methods of calculating stiffness at the vertical and leg levels have also been used in the literature. Coleman et al. (239) compared four different methods of calculating leg stiffness including the methods reported by Morin et al. (209, 243), Blum et al. (255), and Farley et al. (256), with a newly developed "true" stiffness measure. There was a difference of up to 80% between the "true" stiffness and the other measured leg stiffness for over-ground running using force and two-dimensional video data. Many of the calculations used to estimate change in leg length were poorly related to the "true" change in leg length, with change in leg length underestimated by up to 45%.

Assessment of stiffness in running populations have often been performed with one of two approaches: hopping tasks or running over a ground-mounted force plate in discrete trials. These approaches have many limitations to endurance sports such as triathlon. Hopping is often used as a surrogate for running as it can be executed in small spaces and allows a relatively high number of consecutive 'steps' to be obtained (170). Hopping, however is not a routine movement pattern for triathletes. Direct comparisons between stiffness estimates derived from hopping and running have only been reported in the early modelling of human gait using the spring-mass model (170). Over-ground running, on runways between 10 and 60 m long, to land on a force platform, may not replicate the energetic and biomechanical nature of long duration running at a relatively constant speed. Further, over-ground running requiring the athlete to target the force plate may introduce additional variability to the gait of the individual and also limits the number of steps that can be collected and analysed.

An alternative method to investigate the reliability of stiffness measures and compare the different calculations and levels of stiffness for a cohort of triathletes is to use treadmill running. Treadmill running allows a greater number of steps at a consistent velocity to be analysed and limits the effect of natural and imposed gait variation due to targeting the force plate when performing multiple, discrete running trials over shorter distances.

A summary comparing the biomechanical stiffness models and reliability will be a useful guide for sports practitioners. Analysis of individual athletes for performance and injury can be tailored to the athlete and testing environment.

Aim

The study aimed to assess the reliability of different stiffness measures and how they compare to each other. The results should aid researchers in determining the best measure to use to answer the specific question.

Methods

Participants

Twelve well-trained, male triathletes (34±5 years, 75.6±6.2 kg, 1.80±0.04 m) volunteered for the study. All triathletes were currently competitive as top level age group athletes in either Olympic or long distance events. Personal best times in the previous season of under 2 h 20 min for Olympic distance or under 10 h for Iron distance and the ability to run for over 2 min at 4.0 min/km was required. Athletes were excluded if they currently had a lower limb injury or had not been back to full training for at least six weeks following a previous lower limb injury. In order to avoid the possible effects of maturation (198) and ageing (257, 258), athletes under 16 and over 50 were excluded. All athletes provided fully informed written consent prior to participation. Ethical approval was obtained for all testing procedures from the University ethics committee.

Study design

A test-retest between-day protocol on two separate days, seven days apart was performed. Athletes were requested to keep training in the week prior to and following the first training session the same, in order to eliminate the effects of variations in training.

Protocol

A treadmill graded run was performed initially, followed by bent knee and straight knee hopping tasks. Thermal effects on stiffness measures as a result of repeated energy dissipation are unknown, therefore tasks were not randomized. As the hopping task required practice, this was scheduled after the run trial. Running pace was not randomized in order to reduce injury risk. Due to the racing level of the athletes and the distances and speeds experienced in training, this protocol was unlikely to fatigue the athlete and therefore non-randomisation was deemed acceptable. Following warm-up and familiarization of 5 min at 6.0 min/km (2.8 m/s), triathletes ran continuously for 2 min at each of 5.5, 5.0, 4.5 and 4.0 min/km (3.0, 3.3, 3.7 and 4.2 m/s). Cool down consisted of 1 min each at 5.5 min/km and 6.0 min/km. Acceleration and deceleration between running velocity blocks were set to 0.1 m/s^2. Data were collected for the final 20s of each 2 min block to allow gait had stabilized following pace change. Athletes were unaware of when recording was taking place.

After a 5 min rest, triathletes were given as much time as needed to familiarize themselves with hopping in time with the metronome. Athletes performed single leg hopping, first on the right leg and then on the left, on the stationary treadmill (in-ground design with the treadmill belt in line with the laboratory floor). Hopping was carried out first with no instructions other than to keep in time to the metronome set at 2.2 Hz. Hopping was repeated with athletes instructed to keep the knee as straight as possible. Ten hops were recorded once rhythm had stabilized to match the metronome frequency.

During the running and hopping tasks, all triathletes wore spandex shorts or trisuits and their own regular training shoes. Height, weight and bilateral trochanterian height were recorded according to International Society for the Advancement of Kinanthropometry (ISAK) protocols (259). Retroflective markers (10 mm) were attached to the lower body according to a modified three dimensional (3D) model (see Figure 5.2) based on the models reported by Besier et al. (260), Tulchin et al. (261) and Feber et al. (262). Clusters of four markers, on thermo-moulded plastic shells were attached to the posterior pelvis, thigh and shank. Anatomical markers were attached bilaterally to iliacus, anterior superior iliac spine, trochanterion, medial and lateral femoral condyle, medial and lateral malleoli, proximal and distal calcaneus centre, the most anterolateral aspect on the distal border of the calcaneus, 1st and 5th metatarsal heads and centre line of the forefoot between the 2nd and 3rd metatarsal heads. Following a static standing calibration, femoral condyle and malleoli markers were removed. For dynamic calibration of the hip joint, participants moved first the right then the left leg through a combination of flexion, abduction, adduction and extension (260, 263). Knee joint centre dynamic calibration involved three shallow squat movements (260).

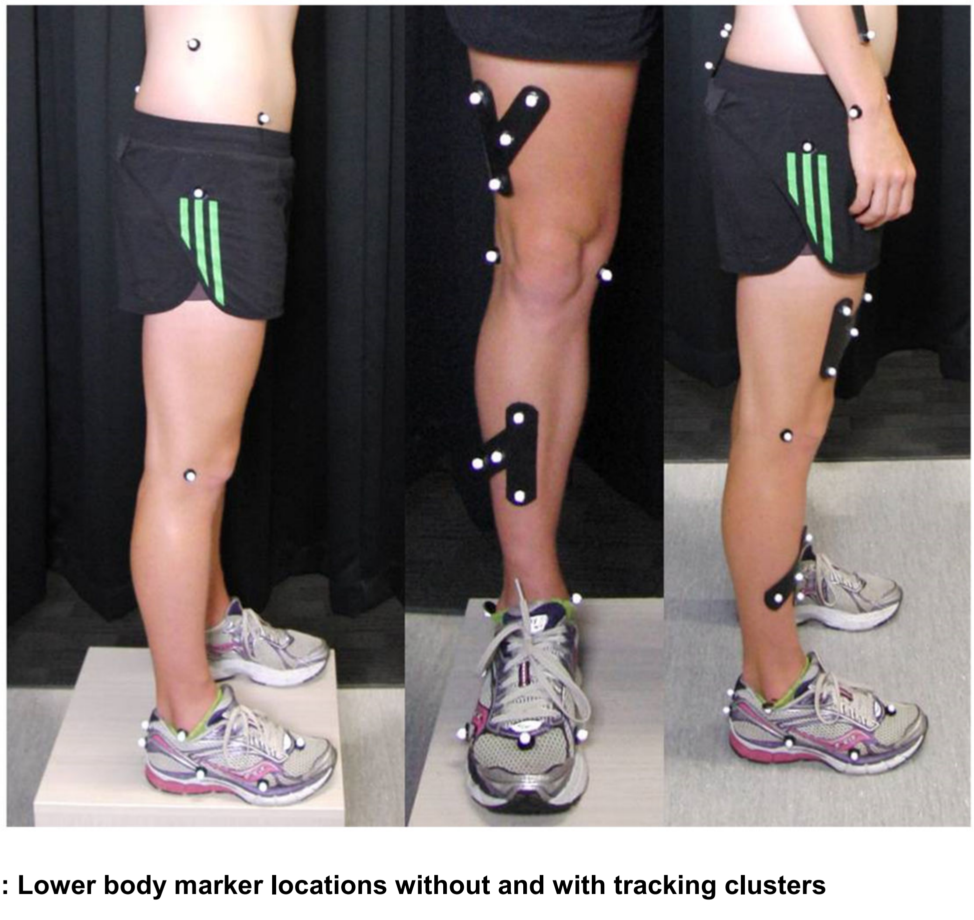

Figure 5.2: Lower body marker locations without and with tracking clusters

Data collection and analysis

A 9-camera VICON motion analysis system (Oxford Metrics Ltd., Oxford, UK) combined with a Bertec instrumented treadmill (BERTEC Corp, Worthington, OH, USA) were used for kinematic (200 Hz) and ground reaction force (1000 Hz) collection, respectively. Functional joint positions were determined using a custom built, MATLAB constrained optimization program (*Optimization Toolbox,* Mathworks Inc.; Natick, MA) detailed by Besier et al. (260). Joint angles, moments and foot centre of pressure locations were calculated via inverse kinematics using Visual3D software (*Visual 3D*, C-motion, Inc.; Germantown, MD). Anatomical co-ordinate systems were defined according to specifications reported by Besier et al. (260). For the single segment foot, the x-axis was the line joining the two calcaneal markers. The y-axis followed the longitudinal axis of the foot from the proximal calcaneal marker, to the forefoot midline marker. The z-axis was orthogonal to the x and y axes.

Variables were averaged over ten steps per leg for each individual for the running trials and five consecutive hops within 5% of the 2.2 Hz hopping frequency. Horizontal velocity was taken as treadmill velocity and was assumed to be constant. Stiffness values were normalized to body weight before statistical analysis.

Stiffness model calculation

Stiffness values were calculated using a custom written Labview program (*Labview,* National Instruments Corp.; Austin, TX). Stiffness was calculated for the first half of stance from initial heel contact to maximal vertical ground reaction force for all stiffness measures (242). Stiffness calculations were carried out using the equations in Table 5.1. The greater trochanter marker was used as reported by Coleman et al. (239) to give $k_{leg/GTR}$. Improved repeatability is reported from using functional hip and knee joints for defining the leg segments (260), therefore the functional hip joint centre (HJC) as the hip marker ($k_{leg/HJC}$) was compared to $k_{leg/GTR}$. Joint stiffness combinations, $k_{sumjoints}$, $k_{hip+knee}$ and $k_{knee+ankle}$ were calculated using equations 1-3.

$$k_{sumjoints} = k_{hip} + k_{knee} + k_{ankle} \qquad (1)$$

$$k_{hip+knee} = k_{hip} + k_{knee} \qquad (2)$$

$$k_{knee+ankle} = k_{knee} + k_{ankle} \qquad (3)$$

Statistical analysis

Descriptive statistics including group means and standard deviations were calculated for all calculations and stiffness levels for both hopping and running. Data were assessed for between trial measurement reliability and measurement variability at the 90% confidence level following log transformation to allow results to be expressed as percentages (264). Robustness was maintained by using two criteria each to determine the level of reliability and variability (265).

Average reliability was determined to be ‘good’ when the percent difference between means (MDiff%) was <5% and the effect size (ES) was trivial (0 – 0.2) or small (0.2 - 0.6) (121). If one of these criteria were not met then measurement reliability was interpreted as ‘average’. ‘Poor’ reliability meant neither criteria was met (265).

Measurement variability was assessed from typical error, reported as coefficient of variation percentage (CV%) (264, 265) and intra-class correlation coefficient (ICC) with upper and lower confidence limits (265). Criteria for 'small' measurement variability were CV <10% (265) and ICC >0.70 (121, 265). If CV was >10% or ICC <0.70 then variability in the measurement was deemed 'moderate'. 'Large' measurement variability was reported if neither criteria for 'small' was met.

For overall reliability all four variables (effect size, percent difference between means, coefficient of variation and interclass correlation) were assessed. 'Good' reliability required all four criteria to be met. 'Moderate' reliability resulted from one criteria outside the limits, while if two or more criteria were outside the limits, a 'poor' overall reliability was recorded (242).

Biomechanical stiffness models were checked for comparability using Pearson's correlation coefficient both within the stiffness type and between stiffness types (vertical with leg stiffness and leg with joint stiffness). Leg stiffness and joint stiffness have different units, therefore results were converted to unitless values prior to comparison using equation 4 (159) and equation 5 (266).

$$Dk_{leg} = \frac{k_{leg} l_0}{mg} \qquad (4)$$

$$Dk_{joint} = \frac{k_{joint}}{(mgl_0)} \qquad (5)$$

A Pearson's correlation coefficient >0.90 was interpreted to show 'very large' correlation between the stiffness models or stiffness types. Between 0.70 and 0.90 indicated 'large' comparability, moderate for 0.50-0.69 while anything below 0.50 indicated a poor correlation between the two variables of interest (121). Hopping data were compared to running data for all calculated variables using the above criteria.

Results

Data for the left leg only are presented in Table 5.2 and 5.3 as both the right and left leg showed similar results across all variables. Running velocity was 5.0 min/km (3.3 m/s) to represent a speed that would be encountered in training and/or racing by both elite and amateur triathletes. Descriptive statistics are presented in Table 5.2 for all variables analysed for the left leg during running (5.0 min/km), hopping with a natural knee bend and hopping with the knee as straight as possible.

Hopping with a straight knee resulted in a reduction in knee stiffness compared to bent knee hopping to give an average value closer to running knee stiffness. Ankle stiffness was lower in both hopping conditions compared to running and did not significantly differ between the two hopping conditions. The combined stiffness of the hip, knee and ankle was also less in straight knee hopping than running. All joint variables were closer to running for straight knee hopping than bent knee. Leg stiffness was more than two-fold greater when using the $k_{leg/true}$ estimation than for $k_{leg/dynamic}$ or $k_{leg/time}$. However, the magnitude of the $k_{leg/true}$ estimate was closer to the combined joint stiffness. Ankle stiffness was greater than knee stiffness during running but this relationship was reversed for both hopping conditions. The variation (% of mean) of knee stiffness was larger than the other two joints and this variation was greatest with straight leg hopping (60%). Variation of the stiffness measurements increased when moving from the “global” vertical stiffness to the more focused joint stiffness.

Table 5.2: Average stiffness for running and hopping tasks in triathletes

Method	Mean (±SD)	Method	Mean (±SD)	Method	Mean (±SD)
Vertical-Run (kN/m/kg)		*Leg–Run* (kN/m/kg)		*Joint–Run* (Nm/°/kg)	
$k_{vert/dynamic}$	0.34±0.06	$k_{leg/HJC}$	0.40±0.10	$k_{sumjoints}$	0.47±0.10
$k_{vert/time}$	0.36±0.05	$k_{leg/GTR}$	0.40±0.11	$k_{ankle+knee}$	0.26±0.05
		$k_{leg/dynamic}$	0.15±0.03	$k_{hip+knee}$	0.33±0.08
		$k_{leg/time}$	0.15±0.02	k_{ankle}	0.14±0.03
				k_{knee}	0.11±0.04
				k_{hip}	0.21±0.07
Vertical-Bent Hop (kN/m/kg)		*Leg–Bent Hop* (kN/m/kg)		*Joint–Bent Hop* (Nm/°/kg)	
		$Hk_{leg/HJC}$	0.23±0.03	$Hk_{sumjoints}$	0.51±0.27
		$Hk_{leg/GTR}$	0.23±0.03	$Hk_{ankle+knee}$	0.41±0.22
		$Hk_{leg/dynamic}$	0.21±0.04	$Hk_{hip+knee}$	0.45±0.22
		$Hk_{leg/time}$	0.22±0.02	Hk_{ankle}	0.10±0.01
				Hk_{knee}	0.17±0.06
				Hk_{hip}	0.31±0.18
Vertical-Straight Hop (kN/m/kg)		*Leg–Straight hop* (kN/m/kg)		*Joint–Straight Hop* (Nm/°/kg)	
		$Hk_{leg/HJC}$	0.24±0.02	$Hk_{sumjoints}$	0.43±0.14
		$Hk_{leg/GTR}$	0.23±0.02	$Hk_{ankle+knee}$	0.22±0.06
		$Hk_{leg/dynamic}$	0.22±0.03	$Hk_{hip+knee}$	0.33±0.12
		$Hk_{leg/time}$	0.23±0.02	Hk_{ankle}	0.10±0.03
				Hk_{knee}	0.13±0.04
				Hk_{hip}	0.20±0.10

A comparison of the different measures, the reliability and measurement variability are reported in Table 5.3. All running vertical and leg stiffness variables showed good overall reliability except for the $k_{leg/true}$ estimates. Good reliability was achieved when the top of the ‘true’ leg was measured from the modelled hip joint centre. When measured from the single trochanterion marker, overall reliability was moderate. Individual joint stiffness ranged from poor to good with the hip having the poorest and ankle having the best overall reliability. Combining the joints as hip, knee and ankle, hip and knee or knee and ankle tended to improve the reliability to moderate to good. Bent knee hopping gave good reliability using the $_{kleg/time}$ and $k_{leg/GTR}$ methods but only moderate reliability for the other leg stiffness measures. All joint stiffness estimates, including joint combinations had poor overall reliability. Straight leg hopping improved the $k_{leg/dynamic}$ estimate reliability but gave only poor to moderate $k_{leg/true}$ reliability. Overall reliability of the ankle was improved with straight leg hopping.

Comparability of hopping and running stiffness was poor for all joint measures when hopping with a bent knee except the ankle which was moderate, and all leg measures for straight knee hopping. Moderate comparability was achieved between bent knee hopping and running for all leg measurements except $k_{leg/GTR}$ which was poor. Conversely, comparisons between straight knee hopping and running were moderate for knee, ankle, hip+knee and sumjoints and large for knee+ankle. Only the hip was poorly correlated with running.

As the middle level of stiffness, leg stiffness estimates were compared with vertical and joint stiffness estimates. The highest correlation with each of the combinations of joints, sumjoints, hip+knee, knee+ankle (r=0.61, r=0.82, r=0.66) was with $k_{leg/time}$. Confidence limits for all joint measurement correlations were large, with this variation smallest between $k_{knee+ankle}$ and $k_{leg/time}$. The time and dynamic methods had large correlations with knee stiffness, however ankle and hip stiffness alone showed poor correlations with leg stiffness. All k_{leg} estimates had large correlations with both $k_{vert/dynamic}$ and $k_{vert/time}$.

Table 5.3: Summary of reliability results for various biomechanical stiffness models with comparison between the different models and stiffness types for running and hopping tasks in triathletes

Method	Comparison with	Pearson's Correlation (CL)	Reliability		Variability		Overall
			MDiff%	ES	CV% (CL)	ICC (CL)	Reliability
Running							
$k_{leg/dynamic}$	-	-	0.2 (-2.5 – 3.0)	0.02 (0.00 – 0.03)	3.6 (2.7 – 3.8)	0.97 (0.90 – 0.99)	Good
Vertical							
$k_{vert/dynamic}$	$k_{leg/dynamic}$	0.89 (0.70 – 0.97)	3.5 (0.4 – 6.7)	-0.18 (-0.21 – -0.15)	4.2 (3.2 – 6.7)	0.95 (0.88 – 0.98)	Good
	$k_{leg/time}$	0.79 (0.45 – 0.93)					
	$k_{leg/HJC}$	0.88 (0.68 – 0.96)					
	$k_{vert/time}$	0.83 (0.57 – 0.94)					
$k_{vert/time}$	$k_{leg/dynamic}$	0.87 (0.64 – 0.96)	0.1 (-3.5 – 3.8)	0.01 (-0.02 – 0.03)	5.2 (3.8 – 8.1)	0.85 (0.62 – 0.94)	Good
	$k_{leg/time}$	0.91 (0.73 – 0.97)					
	$k_{leg/brakeHJC}$	0.87 (0.65 – 0.95)					
Leg							
$k_{leg/GTR}$	$k_{leg/dynamic}$	0.68 (0.25 – 0.89)	-1.4 (-9.2 – 6.9)	0.13 (0.09 – 0.18)	11.8 (8.7 – 18.8)	0.77 (0.46 – 0.91)	Moderate*
	$k_{leg/time}$	0.64 (0.18 – 0.87)					
	$k_{leg/HJC}$	0.97 (0.91 – 0.99)					
$k_{leg/brakeHJC}$	$k_{leg/dynamic}$	0.72 (0.32 – 0.90)	3.2 (-3.7 – 10.5)	-0.11 (-0.17 – -0.06)	9.8 (4.2 – 15.6)	0.85 (0.63 – 0.94)	Good*
	$k_{leg/time}$	0.69 (0.27 – 0.89)					
$k_{leg/time}$	$k_{leg/dynamic}$	0.94 (0.83 – 0.98)	0.3 (-1.8 – 2.4)	-0.00 (-0.01 – 0.01)	2.8 (2.0 – 4.4)	0.98 (0.93 – 0.99)	Good

Table 5.3 cont.: Summary of reliability results for various biomechanical stiffness models with comparison between the different models and stiffness types for running and hopping tasks in triathletes

Method	Comparison with	Pearson's Correlation (CL)	Reliability		Variability		Overall
			MDiff%	ES	CV% (CL)	ICC (CL)	Reliability
Running							
Joint							
$k_{sumjoints}$	$k_{leg/HJC}$	0.55 (0.06 – 0.82)	-5.4 (-10.5 – 0.0)	0.36 (0.32 – 0.40)	7.9 (5.8 – 12.5)	0.86 (0.65 – 0.95)	Moderate*
	$k_{leg/GTR}$	0.39 (-0.13 – 0.75)					
	$k_{leg/dynamic}$	0.49 (-0.05 – 0.81)					
	$k_{leg/time}$	0.61 (0.13 – 0.86)					
$k_{knee+ankle}$	$k_{leg/dynamic}$	0.75 (0.37 – 0.91)	-3.1 (-8.4 – 2.5)	0.18 (0.16 – 0.20)	8.0 (5.9 – 12.7)	0.87 (0.66 – 0.95)	Good*
	$k_{leg/time}$	0.82 (0.52 – 0.94)					
	$k_{leg/HJC}$	0.69 (0.29 – 0.88)					
$k_{hip+knee}$	$k_{leg/dynamic}$	0.53 (0.00 – 0.82)	-5.8 (-11.4 – 0.1)	0.33 (0.29 – 0.37)	8.7 (6.5 – 13.9)	0.88 (0.70 – 0.96)	Moderate*
	$k_{leg/time}$	0.66 (0.21 – 0.88)					
	$k_{leg/HJC}$	0.54 (0.06 – 0.82)					
k_{ankle}	$k_{leg/dynamic}$	0.20 (-0.36 – 0.65)	-4.2 (-10.2 – 2.3)	0.31 (0.30 – 0.33)	9.3 (6.9 – 14.8)	0.75 (0.42 – 0.90)	Good*
	$k_{leg/time}$	0.28 (-0.29 – 0.70)					
	$k_{leg/HJC}$	0.39 (-0.14 – 0.74)					
k_{knee}	$k_{leg/dynamic}$	0.76 (0.40 – 0.92)	-1.3 (-10.2 – 8.4)	0.02 (0.00 – 0.05)	13.8 (10.1 – 22.1)	0.90 (0.73 – 0.96)	Moderate
	$k_{leg/time}$	0.79 (0.46 – 0.93)					
	$k_{leg/HJC}$	0.55 (0.08 – 0.83)					
k_{hip}	$k_{leg/dynamic}$	0.17 (-0.39 – 0.64)	-7.7 (-14.8 – 0.0)	0.43 (0.41 – 0.46)	11.6 (8.5 – 18.5)	0.83 (0.59 – 0.94)	Poor*
	$k_{leg/time}$	0.31 (-0.25 – 0.72)					
	$k_{leg/HJC}$	0.32 (-0.22 – 0.70)					

Table 5.3 cont.: Summary of reliability results for various biomechanical stiffness models with comparison between the different models and stiffness types for running and hopping tasks in triathletes

Method	Comparison with	Pearson's Correlation (CL)	Reliability		Variability		Overall
			MDiff%	ES	CV% (CL)	ICC (CL)	Reliability
Hopping – Bent knee							
Joint							
$Hk_{leg/dynamic}$	$Rk_{leg/dynamic}$	0.66 (0.20 – 0.88)	-7.0 (-11.6 – -2.2)	0.34 (0.32 – 0.36)	5.9 (4.2 – 10.4)	0.92 (0.74 – 0.97)	Moderate
$Hk_{leg/time}$	$Rk_{leg/time}$	0.53 (0.01 - 0.82)	-3.7 (-6.6 – -0.7)	0.51 (0.50 – 0.52)	3.9 (2.8 – 6.4)	0.73 (0.33 – 0.91)	Good*
$Hk_{leg/HJC}$	$Rk_{leg/HJC}$	0.55 (0.07 – 0.82)	-5.5 (-10.1 – -0.7)	0.43 (0.41 – 044)	6.3 (4.5 – 10.5)	0.79 (0.45 – 0.93)	Moderate*
$Hk_{leg/GTR}$	$Rk_{leg/GTR}$	0.34 (-0.20 – 0.72)	-3.5 (-7.7 – 0.9)	0.38 (0.36 – 0.39)	5.5 (4.0 – 9.3)	0.71 (0.30 – 0.90)	Good*
Joint							
$Hk_{sumjoints}$	$Rk_{sumjoints}$	-0.17 (-0.62 – 0.36)	-10.4 (-32.2 – 18.5)	0.03 (-0.11 – 0.17)	13.0 (9.1 – 23.2)	0.52 (-0.07 – 0.83)	Poor*
$Hk_{hip+knee}$	$Rk_{hip+knee}$	-0.31 (-0.70 – 0.22)	-10.4 (-35.4 – 24.3)	0.22 (0.10 – 0.35)	49.1 (33.8 – 92.9)	0.32 (-0.28 – 0.72)	Poor*
$Hk_{knee+ankle}$	$Rk_{knee+ankle}$	0.49 (-0.01 – 0.80)	-4.1 (-32.0 – 35.1)	0.03 (-0.10 – 0.17)	48.0 (32.5 – 95.5)	0.39 (-0.23 – 0.78)	Poor*
Hk_{ankle}	Rk_{ankle}	0.65 (0.23 – 0.87)	-8.2 (-17.5 – –2.1)	0.56 (0.55 – 0.57)	13.0 (9.1 – 23.2)	0.52 (-0.07 – 0.83)	Poor*
Hk_{knee}	Rk_{knee}	0.49 (-0.01 – 0.79)	2.9 (-18.5 – 29.9)	-0.13 (-0.17 – -0.08)	32.9 (23.1 – 59.7)	0.51 (-0.03 – 0.82)	Poor*
Hk_{hip}	Rk_{hip}	-0.38 (-0.74 – 0.15)	-31.9 (-51.5 – -3.6)	0.59 (0.49 – 0.68)	48.1 (32.6 – 95.7)	0.56 (-0.03 – 0.85)	Poor*
$Hk_{knee+ankle}$	$Hk_{leg/time}$	0.46 (-0.12 – 0.81)					

Table 5.3 cont.: Summary of reliability results for various biomechanical stiffness models with comparison between the different models and stiffness types for running and hopping tasks in triathletes

Method	Comparison with	Pearson's Correlation (CL)	Reliability MDiff%	ES	Variability CV% (CL)	ICC (CL)	Overall Reliability
Hopping – Straight knee							
Leg							
$Hk_{leg/dynamic}$	$Rk_{leg/dynamic}$	0.37 (-0.19 – 0.75)	2.8 (-1.9 – 7.7)	-0.18 (-0.20 – -0.16)	5.8 (4.2 – 9.8)	0.91 (0.73 – 0.97)	Good*
$Hk_{leg/time}$	$Rk_{leg/time}$	0.36 (-0.20 – 0.74)	1.1 (-1.6 – 3.9)	-0.14 (-0.15 – -0.13)	5.8 (4.2 – 9.8)	0.85 (0.62 – 0.95)	Good*
$Hk_{leg/HJC}$	$Rk_{leg/HJC}$	0.01 (-0.49 – 0.51)	4.2 (-1.5 – 10.2)	-0.26 (-0.27 – -0.24)	7.1 (5.1 – 12.0)	0.69 (0.24 – 0.89)	Moderate*
$Hk_{leg/GTR}$	$Rk_{leg/GTR}$	0.02 (-0.48 – 0.52)	6.2 (0.8 – 11.8)	-0.50 (-0.51 – -0.48)	6.5 (4.7 – 10.9)	0.69 (0.25 – 0.89)	Poor*
Joint							
$Hk_{sumjoints}$	$Rk_{sumjoints}$	0.63 (0.19 – 0.86)	-2.7 (-13.7 – 22.3)	-0.08 (-0.16 – 0.00)	23.7 (16.8 – 41.9)	0.66 (0.20 – 0.88)	Poor*
$Hk_{hip+knee}$	$Rk_{hip+knee}$	0.61 (0.16 – 0.85)	1.7 (-17.4 – 23.3)	-0.10 (-0.17 – -0.02)	28.9 (20.4 – 51.9)	0.63 (0.15 – 0.87)	Poor*
$Hk_{knee+ankle}$	$Rk_{knee+ankle}$	0.73 (0.35 – 0.90)	8.6 (-12.7 – 35.2)	-0.28 (-0.32 – -0.23)	30.6 (21.5 – 55.2)	0.25 (-0.35 – 0.69)	Poor
Hk_{ankle}	Rk_{ankle}	0.54 (0.05 – 0.82)	-0.8 (-10.8 – 10.4)	0.09 (0.07 – 0.10)	14.8 (10.8 – 24.7)	0.76 (0.42 – 0.91)	Moderate*
Hk_{knee}	Rk_{knee}	0.62 (0.18 – 0.86)	9.6 (-17.5 – 45.7)	-0.33 (-0.37 – -0.29)	44.5 (31.3 – 79.8)	0.14 (-0.38 – 0.60)	Poor
Hk_{hip}	Rk_{hip}	0.47 (-0.03 – 0.79)	-6.6 (-22.6 – 12.7)	0.11 (0.06 – 0.17)	25.8 (18.2 – 45.9)	0.81 (0.49 – 0.93)	Poor*
$Hk_{knee+ankle}$	$Hk_{leg/time}$	0.57 (0.06 – 0.84)					

* at least one reliability parameter was unclear (confidence interval spanned more than one criteria).

Discussion

Consideration of the relationship between the hip, knee and ankle joints and how they contribute to overall leg and vertical stiffness may improve understanding of how each athlete responds to specific variations in the task or environmental constraints. Ankle and knee stiffness have been investigated with leg stiffness, but always as isolated units (183, 240, 242, 252) and the poor reliability of isolated joint stiffness estimates (242) limits the usefulness of such results.

Mean $k_{vert/dynamic}$ was similar to results reported for treadmill running (177). When contact and flight time were used to estimate vertical stiffness ($k_{vert/time}$), stiffness was similar to $k_{vert/dynamic}$ but substantially smaller than the average stiffness reported by Hunter et al. (206) using the same time based calculation method. The lower stiffness in the current research could be the result of using different populations: competitive triathletes versus general runners. Alternatively, use of a measured leg length, in the current data, rather than estimated leg length could account for the differences in stiffness reported. Running speed also varied for the runner population which influencing the vertical stiffness estimates (206, 267).

Mean $k_{leg/dynamic}$ and $k_{leg/time}$ were similar to results for treadmill running (177, 206) but were lower than for over ground running for the respective calculations (180, 239). Treadmill running tends to be more upright with a shorter stride, higher cadence and flatter foot than over ground running (268, 269). Increased cadence is associated with increased k_{leg} (175, 177, 178, 190) however reducing the contact angle of the stance leg may contribute to lower k_{leg} (171, 270). Alternately, the requirements of landing on a force platform in over-ground running also introduces the issue of targeting which could alter landing forces and joint angles at contact, contributing to variations in the stiffness estimates (271). Joseph et al. (242) reported lower $k_{leg/dynamic}$ than the current data for over ground running in middle distance runners. Due to the small sample sizes, population differences would alter the mean stiffness estimates (272). While triathletes do not have significantly different running motor coordination compared to training matched runners, differences are observed between triathletes and novice runners (230). Comparisons between cohorts from various sporting populations and triathletes could therefore explain the difference in k_{leg} observed.

In a comparison of different methods for estimating k_{leg}, Coleman et al. (239) reported 36% greater and 5% lower stiffness for $k_{leg/dynamic}$ and $k_{leg/time}$ respectively, compared to the $k_{leg/true}$ method. Utilising the same concept for calculating "true" leg stiffness, the current data shows more than two-fold greater stiffness than $k_{leg/dynamic}$ or $k_{leg/time}$. During treadmill running, the centre of pressure moves under the centre of mass compared to over ground running where the centre of mass moves over the centre of pressure. As a result the centre of pressure to hip distance (COP distance) will be smaller throughout stance for treadmill running than for over ground running. If joint angles remain constant between the two conditions, a shorter COP distance would produce a longer effective leg and changes in leg length would be smaller for treadmill running.

Average k_{ankle} was similar to results for sprint running (183) but about half the stiffness of over ground running at a similar horizontal velocity (242). The majority of literature reports knee stiffness to be higher than ankle stiffness in over ground running (183, 242). The current cohort of triathletes showed equal group means for ankle and knee stiffness with many individual athletes having lower knee than ankle stiffness. A similar relationship between k_{knee} and k_{ankle} was reported for thirteen runners, running over ground at a range of velocities (180). Increasing the ratio of midfoot and forefoot strikers in the subject population is likely to increase the average knee stiffness and decrease ankle stiffness (273). Further investigation into the relationship between knee and ankle stiffness and how inter-individual variation in factors, such as footstrike patterns, influences this relationship is required.

The results confirm that vertical and leg stiffness have good inter-day reliability. Individual joint stiffness ranged from poor to good. While the measurement reliability (MDiff% and ES) were acceptable for ankle, knee and hip, the knee and hip had large measurement variability (%CV and ICC). When the joints were combined as sumjoints, hip +knee or knee+ankle, variability was reduced to an acceptable level and overall reliability was improved to moderate to good. This result highlights the co-operation of the joints within the kinetic chain to achieve a task goal (79, 160). While determinants of continuous running gait like step length, step rate, ground contact and swing time would appear relatively invariable, the mechanism for achieving a successful braking phase can take many routes responding to altered constraints imposed on the system (160, 274).

Stiffness control is initiated prior to ground contact with muscle pre-activation. The hip and ankle angles set the angle of the leg at contact and therefore the angle of the sweep of the leg (Figure 5.1) (Table 5.1 $k_{leg/dynamic}$). Less hip flexion would result in the centre of pressure at initial contact being further under the centre of mass (Figure 5.1), a smaller angle of the sweep of the leg, and as a result, less ‘leg spring’ compression, if all other factors remain equal. The knee is the link allowing adaptation to the environment following contact and therefore has greater variation than the hip and ankle (275). The current results support control of the kinetic chain in this manner. Correlations of the hip and knee combination (r=0.66) and the three joints combined (r=0.61) with $k_{leg/time}$ were lower than for the knee and ankle combination (r=0.82; 95% CI 0.52-0.94). Knee correlation with $k_{leg/time}$ (r=0.79; 95% CI 0.46-0.93) was similar to the knee and ankle combination indicating that the knee is the primary controller of leg stiffness of triathletes running at the velocities assessed in the present study. However, the ankle may play a small role also. The lower variability (%CV and ICC) achieved, once the joints are combined, highlights the role of individual joint variation in executing a consistent movement pattern.

Reliability of $k_{leg/time}$ and $k_{leg/dynamic}$ were the best with clear, good reliability, followed by $k_{leg/HJC}$ (good, unclear) then $k_{leg/GTR}$ (moderate, unclear). When compared to $k_{sumjoints}$, $k_{leg/time}$ had the best correlations (r=0.61), although the confidence interval was very large. Correlations with $k_{knee+ankle}$ were slightly higher for $k_{leg/time}$ (r=0.82) than $k_{leg/dynamic}$ (r=0.75). Due to the better correlations with all levels of stiffness and the slightly narrower confidence intervals, $k_{leg/time}$ was considered to be the best option for measuring stiffness in triathletes. However, $k_{leg/dynamic}$ is also a good choice giving comparable results.

Leg and joint stiffness can also be measured from hopping tasks. The current data suggests that in triathletes, hopping, either with normal knee bend or a straight knee, does not correlate well with treadmill running for leg and joint stiffness estimates (Table 5.3). Interestingly, bent knee hopping correlates moderately with running for leg stiffness but straight knee hopping has better correlations than bent knee for joint stiffness. Gait has been divided into two models based on the trajectory of the centre of mass, the 'inverted pendulum' for walking (276) and 'bouncing/spring-mass' for running (159, 170, 277). Like running, the centre of mass trajectory during hopping is lowest at the time point of highest vertical force and highest at mid-flight. However, when adding horizontal movement some fundamental differences are introduced to the model. Vertical hopping has a horizontal velocity of ~0 m/s and is characterised by a forefoot landing. Ankle angle, displacement and energy storage are therefore likely to be quite different in hopping than running. With running, a degree of horizontal motion is added to the vertical movement of the centre of mass. Projecting the centre of mass forward necessitates different muscle activity with changes in the electromyography profiles (278). Therefore, hopping may not be a good surrogate for running when estimating leg stiffness.

Besides biomechanical differences between hopping and running, the poor stiffness correlations for these two tasks could be due to the lack of skill the triathletes had for hopping. Hopping was constrained to 2.2 Hz, reportedly preferred hopping frequency, and this constraint may have altered the natural movement of the athlete (241). It should also be noted that stiffness is altered as a result of changing contact time. Therefore the hop or stride frequency would also influence stiffness. In a one hour fatiguing run, runners' preferred stride frequency ranged from 1.36 to 1.60 Hz (206). It is possible that hopping would provide more comparable stiffness estimates if the athletes hopped at their preferred stride frequency.

Conclusions

Due to the superior reliability and correlations with both combinations of joint stiffness and vertical stiffness, the $k_{leg/time}$ method is recommended for assessing leg stiffness. However, $k_{leg/dynamic}$ also appears to be a good measure and when combined with joint angle recording also allows for calculation of joint stiffness. Joints should be assessed as a system in relation to each other rather than in isolation in order to gain acceptable reliability of the measure. The knee and ankle combination appears to be the most important when assessing changes in leg stiffness for triathletes running at the paces assessed in the present study. Hopping at 2.2 Hz is not a good substitute for running when estimating stiffness in triathletes. Further analysis is required to determine if hopping correlates with running when frequency is constrained to the athletes preferred stride rate.

CHAPTER 6

LOWER LIMB STIFFNESS IS AFFECTED BY RUNNING PACE IN TRIATHLETES

This chapter comprises the following paper:

Lorimer, A., Hume, P., Keogh, J. Lower limb stiffness is affected by running pace in triathletes**.** To be submitted to *Journal of Science and Medicine in Sport*.

Overview

Aim: To determine the effect of increasing running pace on vertical, leg, hip, knee and ankle stiffness and different joint combinations.

Methods: Three-dimensional video and force data were collected for 75 triathletes running on a treadmill at four velocities (3.0, 3.3, 3.7 and 4.2 m/s). The average of ten steps on the left leg were analysed at each velocity. Vertical, leg, hip, knee and ankle stiffness were calculated.

Results: Vertical (ES=0.69; 90% CI 0.68-0.71 for 4.5-4.0 min/km pace change), knee (0.37; 0.36-0.39) and ankle (0.51; 0.50-0.52) stiffness increased with increasing velocity. Leg (0.08; 0.08-0.09) and hip (0.04; 0.04-0.06) stiffness remained constant.

Discussion: If increasing stiffness is associated with an increased risk of Achilles tendon injuries, then running for extended periods at faster paces may increase an athlete's risk of injury. The starting pace and the magnitude of the velocity increase influenced the magnitude of the stiffness change of the individual joints. Athletes use a wide variety of combinations of stride length and stride rate in order to achieve a given running pace. It is possible that knee stiffness increases more in response to increasing stride rate than to increasing stride length. Changing the balance between knee and ankle stiffness may lead to increased shearing or torsional stress within the Achilles tendon, increasing injury risk.

Conclusion: Increasing running pace in triathletes resulted in increased vertical, knee and ankle stiffness. Increased lower limb stiffness is a potential injury risk factor, therefore running athletes who always run at a fast pace may be at increased risk of injury. Further understanding of the relationship between joint stiffness, stride length and stride rate may provide information on an athlete's risk of injury and allow coaches to tailor training accordingly.

Introduction

Achilles tendon injuries are problematic in triathletes (16, 161). While a number of intrinsic and extrinsic risk factors have been suggested, high braking forces, low surface stiffness and low arches were shown to be independently associated with increased risk of injury (167). An overuse injury could result from a number of individually undetectable, but collectively injurious movements that load particular anatomical structures beyond their capacity (79). This loading may reflect the demands of the task and environment and/or be inherent to the individual. Therefore, a multifactorial risk factor analysis approach may provide better insight into what leads to injury in some athletes.

Running has been successfully modelled using the ‘spring-mass’ model, in which a point mass is supported by a compressible spring with the mechanical property, stiffness (k) (159, 170). Compression of the ‘leg spring’ is achieved through rotation of the joints which are modelled as torsional springs resisting rotation (240, 244). Both high and low stiffness of the lower body has been proposed to be risk factors for injury (80, 137, 148, 149). Individuals with Achilles tendon injuries had significantly higher leg stiffness compared to uninjured during hopping (157). Many of the identified risk factors for Achilles tendon injuries potentially increase the stiffness of the lower body during running or hopping (279). Both vertical and leg stiffness have well established reliability, however, joint stiffness reliability is poor in overground running and hopping (242). For treadmill running, ankle stiffness had good-moderate reliability, however, reliability for knee stiffness was moderate and poor for the hip (280). When combined as sumjoints, hip+knee or knee+ankle then reliability was improved, particularly for the knee+ankle combination which had a good-moderate reliability rating (280). Based on correlations with leg stiffness, calculated using the $k_{leg/time}$ method (Table 6.1), the knee and ankle appear to have the most influence over leg stiffness (280).

Running pace is important for triathlon performance, however a rapid increase in training intensity may be involved in Achilles injuries (126, 128, 129, 136). A smaller difference between training pace and race pace was found in individuals who had chronic Achilles injuries compared to uninjured runners (136), suggesting that athletes who do not utilise a wide variety of training paces are more susceptible to injuries. Changing running velocity and its effect on vertical, leg and joint stiffness, has been investigated in small groups for both sprinting and running (175, 178, 180-183, 215). However, only one study, looking at the correlation between velocity and vertical stiffness over the course of a 5000 m time trial showed a clear, increase in stiffness with increasing velocity (175, 279). Only a small range of velocities occurred in this situation. In order to increase pace athletes must increase stride rate and/or stride length with a resulting decrease in contact time. Increasing stride rate and decreasing contact time was associated with increased stiffness however increasing stride length showed variable changes to stiffness (279). The effect of velocity on joint stiffness has been investigated in only two studies (180, 183), with knee and ankle stiffness both increasing slightly with running velocity (180), but only the knee stiffness increasing with increasing sprint velocity (183). The effect of velocity on hip stiffness or on combinations of the joints has to our knowledge not been investigated.

Table 6.1: Biomechanical stiffness model calculations, variables and equipment

Stiffness calculation	Terms list	Key variables
Vertical stiffness		
$k_{vert/time} = \frac{F_{max}}{\Delta y}$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta y = -\frac{F_{max}}{m}\frac{t_c^2}{\pi^2}+g\frac{t_c^2}{8}$	F_{max} = peak vertical force, Δy = centre of mass displacement, m = subject mass, t_c = contact time, t_f = flight time, g = acceleration due to gravity.	Contact time (243)
Leg stiffness		
$k_{leg/time} = \frac{F_{max}}{\Delta L}$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta y = -\frac{F_{max}}{m}\frac{t_c^2}{\pi^2}+g\frac{t_c^2}{8}$ $\Delta L = L_0 - \sqrt{L_0^2-\left(\frac{vt_c}{2}\right)^2}+\Delta y$	F_{max} = peak vertical force, ΔL = change in leg length, Δy = centre of mass displacement, L_0 = trochanterian height, m = subject mass, t_c = contact time, t_f = flight time, g = acceleration due to gravity, *v* = horizontal velocity	Contact time Horizontal velocity Standing leg length (243)
Joint stiffness		
$k_{joint} = \frac{\Delta M}{\Delta \theta}$	ΔM = change in joint moment, Δθ = change in joint angle	Three dimensional force Lower body video for inverse dynamics calculation (240, 244)

Aim

The objective of the study was to determine the effect of increasing running pace on vertical, leg, hip, knee and ankle stiffness and combinations of joint stiffness.

Methods

Athlete characteristics

Seventy-five triathletes (45 male; 34.1±9.9 years, 76.1 ±7.1 kg, 1.80 ±0.06 m and 30 female; 31.0±8.3 years, 62.1 ±5.6, 1.69 ±0.06 m) volunteered for the research. All were currently professional or top level age group Olympic or long distance triathletes. Personal best times in the previous season of 2h 20 min/ 2h 40 min (male/female) for Olympic distance or 10 h/ 11h 30 min (male/female) for Iron distance and the ability to run for over 2 min at 4.0 min/km was required. Triathletes were free from lower limb injuries at the time of testing and had been back to full training for at least six weeks following any previous injury. All athletes provided fully informed written consent prior to participation. Ethical approval was obtained for all testing procedures from the university ethics committee.

Procedures

A treadmill graded run task was performed without randomization to allow inter-subject comparisons. Following warm-up and familiarization of five minutes at 6.0 min/km (2.8 m/s), triathletes ran for two minutes each at 5.5, 5.0, 4.5 and 4.0 min/km (3.0, 3.3, 3.7 and 4.2 m/s). A jogging or walking cool-down was given. All acceleration and deceleration between running velocity blocks were set to 0.1 m/s^2. Data were collected for the final 20 s of each two minute block in order to ensure gait had stabilized following pace change. Athletes were unaware of when recording was taking place.

All triathletes wore spandex shorts or trisuits and their own regular training shoes. Height, weight and bilateral trochanterian height were recorded according to International Society for the Advancement of Kinanthropometry (ISAK) protocols. Retroflective markers (10 mm) were attached to the lower body according to a modified three dimensional (3D) model (see Figure 6.1) (280).

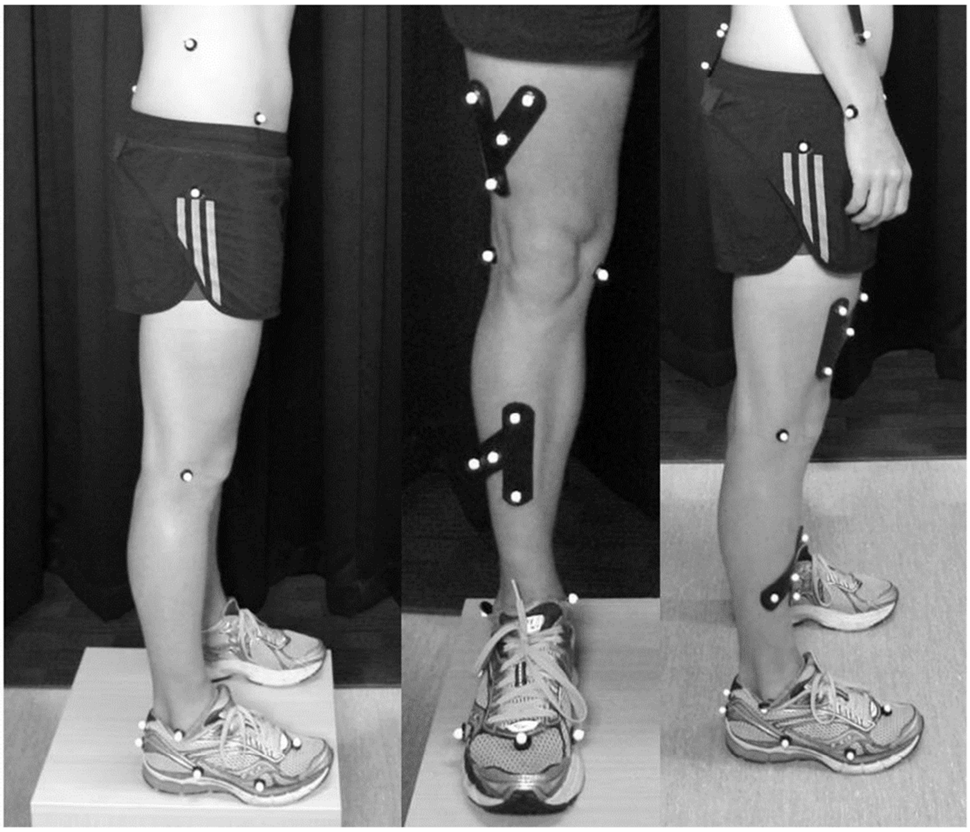

Figure 6.1: Lower body marker locations without and with tracking clusters

Data collection and analysis

A 9-camera VICON motion analysis system (Oxford Metrics Ltd., Oxford, UK) combined with a Bertec instrumented treadmill (BERTEC Corp, Worthington, OH, USA) were used for kinematic (200 Hz) and ground reaction force (1000 Hz) collection, respectively. Functional joint positions were determined using a custom built, MATLAB constrained optimization program (*Optimization Toolbox,* Mathworks Inc.; Natick, MA) detailed by Besier et al. (260). Joint angles and moments were calculated via inverse kinematics using Visual3D software (*Visual3D™,* C-motion, Inc.; Rockville, MD). Anatomical co-ordinate systems were defined according to specifications reported by Besier et al. (260) and Lorimer et al. (280).

Variables were averaged over ten consecutive steps for the left leg for each individual. Horizontal velocity was taken as treadmill velocity and was assumed to be constant. Stiffness values were normalized to body weight before statistical analysis.

Stiffness calculations

Stiffness values were calculated using a custom written Labview program (*Labview,* National Instruments Corp.; Austin, Tx). Stiffness was calculated for the first half of stance from initial heel contact to maximal vertical ground reaction force for all stiffness measures (242). Stiffness calculations were carried out using the equations in Table 1.

Joint stiffness combinations, $k_{sumjoints}$, $k_{hip+knee}$ and $k_{knee+ankle}$ were calculated using equations 1-3.

$$k_{sumjoints} = k_{hip} + k_{knee} + k_{ankle} \qquad (1)$$

$$k_{hip+knee} = k_{hip} + k_{knee} \qquad (2)$$

$$k_{knee+ankle} = k_{knee} + k_{ankle} \qquad (3)$$

Statistical analysis

Descriptive statistics for all variables were calculated. Changes in stiffness with increases in running pace were calculated as effect sizes with 90% confidence intervals Effect size thresholds were 0.2, 0.6, 1.2 and 2.0 for trivial, small, moderate and large (121).

Results

Sixty-six triathletes (44 male, 29 female) had viable data at 5.5 min/km, 67 (45 M, 30 F) at 5.0 min/km, 64 (43 M, 30 F) at 4.5 min/km and 50 (35 M, 21 F) at 4.0 min/km. There were variable numbers of athletes with viable data due to some initial problems with data collection. As a result, some trials had insufficient consecutive steps. Differences between males and females were trivial, therefore data for men and women were combined. Stiffness means and standard deviations are presented in Table 6.2.

Table 6.2: Means and standard deviations for lower body stiffness measures with increasing running pace

	Running pace [min/km (m/s)]			
Stiffness measure	5.5 (3.0)	5.0 (3.3)	4.5 (3.7)	4.0 (4.2)
$k_{vertical/time}$ (kN/m/kg)	0.37 ±0.04	0.39 ±0.05	0.42 ±0.05	0.48 ±0.06
$k_{leg/time}$ (kN/m/kg)	0.17 ±0.02	0.16 ±0.02	0.16 ±0.02	0.17 ±0.03
$k_{sumjoints}$ (Nm/°/kg)	0.46 ±0.09	0.47 ±0.14	0.49 ±0.10	0.54 ±0.10
$k_{hip+knee}$ (Nm/°/kg)	0.33 ±0.08	0.34 ±0.13	0.35 ±0.08	0.37 ±0.09
$k_{knee+ankle}$ (Nm/°/kg)	0.26 ±0.06	0.27 ±0.07	0.29 ±0.07	0.33 ±0.08
k_{hip} (Nm/°/kg)	0.20 ±0.06	0.21 ±0.11	0.20 ±0.07	0.21 ±0.07
k_{knee} (Nm/°/kg)	0.13 ±0.05	0.13 ±0.05	0.15 ±0.06	0.17 ±0.07
k_{ankle} (Nm/°/kg)	0.13 ±0.03	0.13 ±0.03	0.15 ±0.03	0.16 ±0.04

Vertical, knee and ankle stiffness increased with increasing pace (Table 6.3). The magnitude of the increases in vertical, knee and ankle stiffness were not dependent on the size of the velocity increase. Ankle stiffness increased for all pace changes. Knee stiffness changes were trivial for the first two pace changes (5.5-5.0 and 5.0-4.5 min/km) however all subsequent pace adjustments gave small to moderate effect size increases. As a result, the change in combined knee and ankle stiffness was trivial for the first pace change but small to moderate for all subsequent pace changes. Leg stiffness was only effected by two pace changes, 5.5-5.0 and 5.5-4.5 min/km. Hip stiffness remained unchanged for all pace changes.

Table 6.3: Magnitude of changes in stiffness for treadmill running with increasing pace in triathletes, effect size with 90% confidence intervals

	5.5 - 5.0 min/km Effect size (Lower:Upper CL)	5.0 - 4.5 min/km Effect size (Lower:Upper CL)	4.5 - 4.0 min/km Effect size (Lower:Upper CL)	5.5 - 4.5 min/km Effect size (Lower:Upper CL)	5.0 - 4.0 min/km Effect size (Lower:Upper CL)	5.5 - 4.0 min/km Effect size (Lower:Upper CL)
Δ Pace	30 sec/km	30 sec/km	30 sec/km	60 sec/km	60 sec/km	90 sec/km
Δ Velocity	0.3 m/s	0.4 m/s	0.5 m/s	0.7 m/s	0.9 m/s	1.2 m/s
$k_{vertical/time}$	0.24 (0.22:0.26)	0.69 (0.55:0.59)	0.93 (0.71:0.75)	1.11 (0.82:0.85)	1.62 (1.24:1.28)	2.05 (1.53:1.57)
$k_{leg/time}$	-0.20 (-0.21:-0.20)	-0.06 (-0.07:-0.05)	0.08 (0.08:0.09)	-0.26 (-0.27:-0.25)	0.03 (0.02:0.04)	-0.16 (-0.17:-0.15)
$k_{sumjoints}$	0.12 (0.09:0.15)	0.16 (0.13:0.19)	0.44 (0.40:0.47)	0.35 (0.33:0.38)	0.51 (0.48:0.55)	0.81 (0.78:0.84)
$k_{hip+knee}$	0.07 (0.04:0.10)	0.08 (0.05:0.11)	0.31 (0.29:0.34)	0.20 (0.18:0.23)	0.31 (0.28:0.34)	0.52 (0.50:0.55)
$k_{knee+ankle}$	0.13 (0.11:0.15)	0.31 (0.29:0.33)	0.54 (0.51:0.56)	0.44 (0.42:0.46)	0.87 (0.84:0.89)	1.00 (0.98:1.03)
k_{hip}	0.07 (0.04:0.09)	-0.03 (-0.05:0.00)	0.04 (0.02:0.06)	0.05 (0.03:0.07)	0.01 (-0.02:0.03)	0.10 (0.08:0.12)
k_{knee}	0.03 (0.02:0.05)	0.19 (0.18:0.21)	0.37 (0.36:0.39)	0.23 (0.21:0.24)	0.57 (0.55:0.59)	0.61 (0.59:0.63)
k_{ankle}	0.22 (0.22:0.23)	0.34 (0.33:0.35)	0.51 (0.50:0.52)	0.56 (0.55:0.57)	0.87 (0.86:0.88)	1.11 (1.10:1.12)

Shaded squares indicate a clear effect with the lightest shading indicating a small effect size while the darkest shading represents a very large effect size.

Discussion

Two studies examining stiffness changes with increasing velocity used similar running velocities to those in this study (180, 215), although both had smaller sample sizes (n=13 and 7). The average leg stiffness of athletes in our study was lower than previous studies by 0.04 to 0.05 kN/m/kg (24-31% lower). The magnitude of these between-study differences in stiffness are likely the result of different experimental procedures. Arampatzis et al. (180) used overground running and the McMahon and Cheng method (159) to estimate changes in leg length. Lipfert et al. (215) used treadmill running and calculated leg length as the straight line distance between the centre of mass and centre of pressure. It is also possible that the different populations used resulted in different gait patterns with Lipfert et al. (215) using individuals with no specific running experience and Arampatzis et al. (180) utilising runners (unspecified distance). Muscle activity patterns were found to be different in less trained runners, however triathletes and equally trained runners showed no difference in muscle activity profiles (281). A difference in gait pattern is possible between the triathletes in this study and those of Lipfert et al. (215) based on the runners skill. Ankle stiffness for overground running in experienced runners was higher than knee stiffness (180), however both joints had similar stiffness in the current study.

Vertical, knee and ankle stiffness increased with increasing pace, however did not show a linear increase with the size of the velocity increment. Vertical and ankle stiffness effect sizes levelled off for the 0.5 and 0.7 m/s increases (4.5-4.0 and 5.5-4.5 min/km pace changes). The effect size for knee stiffness for the 0.7 m/s increase in velocity was smaller than for the 0.5 m/s increase. Increasing running pace can be achieved via increasing step rate or increasing step length. Hopping and running studies have demonstrated that increasing stride rate and/or decreasing contact time results in increased vertical (175, 177, 178, 189, 190, 206), leg (175, 178, 181, 185-187, 189, 190, 192, 193, 206) and knee and ankle stiffness (183, 186-188). In contrast, correlations between stride length and stiffness gave both increased (175, 181) and decreased (176, 178) vertical stiffness and decreased (178) or unchanged leg stiffness (175, 181). If only stride rate is increased in order to achieve an increased running pace then stiffness would be expected to increase. However, using an increase in stride length or a combined increase in stride rate and length may change the relationship between velocity and lower body stiffness measures.

Increasing stride rate requires a shorter stance time which can be achieved through reducing the vertical displacement of the centre of mass, and rotation of the joints both resulting in increased stiffness (191, 246). A stiffer spring recoils faster under the same load. Increased stride rate can also be achieved with a shorter stance distance coming from a steeper angle of attack. Unless flight time is increased this modification would reduce stride length, negatively impacting velocity.

The relationship between stride length and stiffness appears to be more varied. However, only correlation studies have been reported to date which do not take into account modified stride rate (175, 176, 178, 181). Increased stride length is associated with a shallower angle of attack and a greater COM to COP horizontal distance at touchdown. Stance distance and COM trajectory are longer allowing for greater vertical COM displacement (191). If overstriding occurs then an even greater vertical COM displacement is predicted as the athlete has to move the COM up and over the stance leg. Vertical and leg stiffness would therefore be reduced. Alternatively, stride length can be increased through greater flight distance, which is aided by increased stiffness. A stiff ‘leg spring’ improves energy storage during the first half of stance and return during the propulsive phase producing greater power for a similar energy output. When increasing running pace, athletes use a wide variety of stride length and rate combinations (191), which could explain the varying results previously reported. Confounding the matter further, is the variety of methods for estimating leg stiffness. When the COM is used to estimate change in leg length, vertical displacement plays a large role in the stiffness estimate. However, when leg length is measured from the hip to the COP, the angle of attack and COM to COP distance play a larger role. This could explain why leg stiffness did not increase with velocity when using the McMahon and Cheng model (159) but increased when COP was taken into account (180).

Leg stiffness showed small decreases for the 5.5-5.0 min/km pace change and the 5.5-4.5 min/km pace change. The stiffness decreases could be insignificant or could indicate that the starting pace determines whether changes to leg stiffness are required. When calculating stiffness using the k_{time} method, the difference between leg stiffness and vertical stiffness is the additional consideration of horizontal velocity which determines the angle of the swing of the leg (θ)(243). This angle then influences the orientation of the 'leg spring' at ground contact, initial leg length and therefore the magnitude of possible compression of the 'leg spring'. In a running athlete, the hip motion prior to contact, both in terms of the recovery swing and leg retraction (270), is instrumental in determining this 'leg spring' orientation at ground contact. Running at a slow pace could cause the athlete to shorten their stride, adopting a steep contact angle. An increase in pace which causes the athlete to adopt a flatter contact angle could result in the observed decrease in leg stiffness. The final pace change (5.5-4.0 min/km) which also starts at the slowest pace showed only a trivial leg stiffness decrease. Other gait pattern changes are likely to play a more dominant role for this very large pace change.

Hip stiffness remained unchanged regardless of the magnitude of the pace change. Ankle stiffness increased for all pace changes while knee stiffness increases were trivial for the first two pace changes. The hip is instrumental in determining the angle of attack and therefore the stance distance and trajectory of the COM. However, changes that occur at the hip to facilitate increased running pace are primarily during the flight and propulsive phases and do not register as changes in hip stiffness, measured during the absorption phase. The knee and ankle contribute significantly to impact absorption, accounting for the different profile compared to the hip.

With a constant velocity, increased stride rate results in greater knee flexion at touchdown, smaller knee flexion excursion, decreased dorsiflexion at touchdown and smaller COM to COP distance (246, 282, 283). Combined with reduced peak vertical ground reaction force (246, 283), lower knee and ankle stiffness results. Ankle energy absorption remains relatively stable regardless of the stride rate, however knee energy absorption increases with decreasing stride rate (246). At higher stride rates the ankle plays a larger relative role in energy absorption, approximately equal the knee, but as stride rate decreases the knee becomes more dominant (246).

A negative interaction between stride length and stride rate has been well established (191). Increasing stride length above preferred levels while maintaining preferred running pace resulted in increased mean ankle dorsiflexion moment and mean knee flexion moment (284). Ankle dorsiflexion at touch down is increased with greater stride length however knee flexion is reduced (246). Peak knee flexion is increased resulting in a greater knee flexion excursion offsetting the increased stiffness that would result from greater knee flexion moment (246). Ankle joint excursion changes with increasing stride length were not reported however, energy absorption at the ankle remained constant for all stride lengths/rates (246). In contrast, energy absorption at the knee increased with increasing stride length (246) suggesting greater joint excursion is associated with greater energy absorption. If joint excursion at the ankle stays relatively constant but joint moment increases then ankle stiffness would be expected to increase with increasing stride length.

In the current results, ankle stiffness showed a small increase in stiffness for the first two pace changes (5.5-5.0 and 5.0-4.5 min/km), however, changes in knee stiffness were trivial until the pace change 4.5-4.0 min/km. A combination of increasing stride rate and increasing stride length is assumed to be used by the athletes in order to achieve stable running at the new pace. The lack of change in knee stiffness could be interpreted as an increase in stride length being the dominant mechanism for increasing pace. As the pace increases further, an increase in stride rate is also required in order to achieve stable running which requires an increase in knee stiffness.

Decreasing knee flexion results in reduced active insufficiency and greater force production from the gastrocnemius. During running gastrocnemius activity occurs earlier than soleus activity resulting in high gastrocnemius activity throughout the lengthening phase of the stretch shorten cycle (285). Soleus activity is low at the start of lengthening increasing activity, to peak just prior to the initiation of shortening (285). Both the gastrocnemius and the soleus insert into the Achilles tendon, therefore different fascicles within the Achilles are loaded differently. Altering the balance of the knee and ankle contribution could increase the risk of injury to the Achilles tendon by increasing shearing or creating an uneven torsional load within the tendon (74).

Vertical, knee and ankle stiffness increased with the running paces examined in this study. The magnitude of the change was not dependent on the size of the velocity increment as might be expected. The pace change 5.5-4.5 min/km had a smaller or similar effect size to the pace change 4.5-4.0 min/km despite the respective velocity increments being 0.7 and 0.5 m/s. The starting pace is important in determining whether stride rate or stride length increases are the dominant method of increasing horizontal velocity. The pace change 5.5-4.5 min/km likely requires a bigger stride length change compared to the 4.5-4.0 min/km pace change where an increase in stride rate is more dominant. Increasing stride length appears to have either a negative or a minimal effect on the stiffness measures. A stride-length dominant mechanism of increasing velocity would result in smaller stiffness increases compared to a stride rate dominant mechanism.

The different risk factors for Achilles tendon injury appear to have variable effects on stiffness measurements during running and hopping (167, 279). An increase in stiffness may be associated with increased injury risk (279). It is acknowledged that an increase in stiffness is also required for improved performance. Both the starting pace and the magnitude of the velocity increase appear to be important in determining whether an increase in knee stiffness is required and the magnitude of change to vertical, knee and ankle stiffness. It is hypothesised that the knee does not change stiffness significantly when stride length is increased but does increase stiffness in order to increase stride rate. Athletes should therefore be encouraged to utilise a wide range of velocities during training in order to strengthen the muscles of the different joints and distribute load. Running with an increased stride length may reduce the load at the knee however the ankle load is relatively higher. Preventing overstriding and therefore increased braking forces is also important (167). Running within a narrow pace range is likely to increase the risk of overuse injuries as the gait movement pattern is more confined and invariant, localising stress to a smaller tissue range.

Running velocity was based on even increments in pace which resulted in uneven increments in velocity. While this has led to an observation of differing effect size magnitudes depending on the magnitude of the velocity change, these findings need to be confirmed using even velocity increments over a large pace range. More data points over a greater range of running velocities would allow for a more in depth understanding of the mechanics involved in running at different paces and how this modifies the stress to the different tissues of the body. Further research is required looking at the relationship between stiffness, stride rate and stride length. Understanding how stride rate and stride length alter joint stiffness and the parameters of pace that lead to utilising one mechanism over another would give better insight into how changes in pace may contribute to injury risk. Coaches and practitioners would then be able to prescribe training that provided well balanced distribution of load.

Conclusions

The sample of 75 triathletes utilised in this study has provided insight into the influence of pace changes on the various measures of stiffness. Increasing pace causes an increase in vertical, knee and ankle stiffness but is magnitude and starting pace dependent. Different velocity increments resulted in varying stiffness change and therefore different stress to the body. It is important that athletes utilise a range of paces in training in order to distribute the load as much as possible and vary the stress on the tissues of the legs.

CHAPTER 7

RELIABILITY AND VARIABILITY OF LOWER LIMB STIFFNESS WITH CHANGES IN RUNNING PACE FOR TRIATHLETES

This chapter comprises the following paper:

Lorimer, A., Hume, P., Keogh, J. Reliability and variability of lower limb stiffness with changes in running pace for triathletes. To be submitted to *Sports Biomechanics*.

Overview

Aim: Investigate the reliability of stiffness measures over a range of running paces and how changing pace alters the between-athlete variability of stiffness.

Methods: Three-dimensional video and force data were collected for 75 triathletes running on a treadmill at four paces (5.5, 5.0, 4.5 and 4.0 min/km). Average of ten steps on the left leg were analysed at each velocity. Test-retest reliability for 12 male triathletes was assessed at each pace. The within (10 steps) and between athlete coefficient of variation (CV%) for each pace was calculated for vertical, leg, hip, knee and ankle stiffness.

Results: Reliability was largely unaffected by increasing running pace. Knee stiffness reliability was moderate to poor. Reliability was acceptable when combining knee and ankle stiffness. Between-athlete vertical, leg, knee and ankle stiffness variability was relatively stable across all paces. Within-athlete hip stiffness had the highest variability. However, between-athlete stiffness variability was highest for the knee. The within-athlete variability for the knee and ankle stiffness demonstrated a slight ‘U-shape’.

Discussion: Vertical, leg and combined knee and ankle stiffness measures maintained reliability with increasing pace and therefore are suitable for use in screening a wide range of athletes of varying distance speciality and skill. Between-athlete stiffness variables (except for hip) remained relatively stable over the range of paces measured. Identifying outliers from the general pattern of stiffness adaption with increasing velocity may highlight potentially injurious gait patterns. The knee had the highest between-athlete variability confirming its primary importance in the control of leg stiffness during running. Different running paces provide the athlete with different levels of movement variability and therefore athletes should be encouraged to utilise a wide range of running paces during training to reduce the risk of accumulating tissue damage. Extremely large variability however may indicate running paces at which the athlete’s coordination skill is lacking. Prolonged periods at high paces may increase the risk of injury.

Conclusion: Vertical, leg and combined knee and ankle stiffness appear to be viable measures for screening athletes over a range of running paces. Athletes appear to adapt stiffness using similar methods in order to increase pace resulting in stable between-athlete stiffness. Therefore, outliers from the general pattern of stiffness change may indicate injurious gait patterns. Athletes should be advised to utilise the widest range of running paces possible during training in order to encourage movement variability and reduce tissue overloading. However, extremely large variability may increase injury risk, therefore ensuring athletes maintain good form at faster paces is important.

Introduction

Overuse injuries are the most common injuries in running populations (125), with Achilles tendon injuries being among the most common and most severe for triathletes (16). Achilles tendon injuries due to their reoccurring nature present a large economic, psychological and heath burden. The mechanism of the injury and why some athletes are more susceptible to injury remains unclear. Individual risk factor analysis has limited predictive ability for injury risk, with only increased braking force, low surface stiffness and low arches showing clear increased (167). High vertical and propulsive forces were protective for the Achilles tendon (167). The progressive nature of overuse injuries suggest that relatively small changes in gait may be responsible. It is likely that a collection of biomechanical, environmental, and task specific risk factors come together to influence injury risk (116, 286). Variability in movement patterns, especially highly repetitive movements such as running have been suggested to be protective against overuse injuries by increasing the distribution of the training load over a wide range of tissues (79, 155). Therefore, greater step-to-step variation within an individual could limit injury risk.

Bernstein's (287) theory on coordination and movement control suggests that when learning a movement pattern, the variability possible (degrees of freedom) is limited and increased as skill improves (288). Individuals utilise a failure-adaptation learning process in order to learn the optimal movement pattern based on their personal constraints (289). Gait is learned early in development and is a fundamental movement pattern for most people. However, even a highly repetitive movement such as gait has measurable variability in how the different segments and tissues of the body work together to reach the end goal.

Running is a cyclic movement with a common gross movement pattern, repeated over many cycles. Investigation into the muscular control of running tends to focus on preactivation activity prior to ground contact, and reflex responses during stance (249, 290, 291). Central pattern generator theory suggests that highly repetitive movements may be controlled by a pattern of action potentials which are centrally derived (172, 173).

Control of gait has also been investigated based on reflexes alone (171, 266, 270). Stable running was achieved through reflex control of the 'leg spring', as long as angle of attack (α), leg stiffness (k_{leg}) and velocity parameters were optimized (171). With increasing velocity, increased variability in leg stiffness and angle of attack were tolerated generating bands of spring-mass parameters within which running was stabilised. A minimum speed of ~3.5 m/s was required (171). When complexity of the model was increased to two segments connected by a knee joint, limits to velocity were found which could only be overcome by increasing knee stiffness (266). Plotted human data (n=7) tended to cluster near the minimum knee stiffness required for stable running at a given velocity (266).

Changes in joint stiffness with increasing pace (5.5 – 4.0 min/km) from a large population of triathletes (n=75) appears to be dependent on the magnitude of the increase, and starting pace (292). Different sized increments in velocity (i.e. 0.3-1.2 m/s increases) resulted in variable stiffness effect sizes. It was hypothesised that different mechanisms are involved in achieving changes in velocity of different magnitudes. The variability of stiffness during running at different velocities in a population has to our knowledge not been reported. Variations in gait movement patterns under different task constraints (i.e. increasing pace) may give insight into how these task constraints influence injury risk.

In order for stiffness to be a useful measure for assessing athlete injury risk, reliability of the measure over a variety of paces is required. Athletes can then be tested over the range of running paces that are encountered in training and racing, increasing the ecological validity of the test.

Aim

The aim of this study was to determine how the reliability and variability of lower body stiffness measures changed with altered pace during treadmill running in triathletes.

Methods

Athlete characteristics

Seventy-five triathletes (45 male; 34.1±9.9 years, 76.1 ±7.1 kg, 1.80 ±0.06 m and 30 female; 31.0±8.3 years, 62.1 ±5.6, 1.69 ±0.06 m) volunteered for the research. All triathletes were currently competitive as professional or top level age group athletes with both Olympic distance and long distance athletes included. Athletes were required to have a personal best times in the previous season of 2h 20 min/ 2h 40 min (male/female) for Olympic distance or 10 h/ 11h 30 min (male/female) for Iron distance and the ability to run for over two minutes at 4.0 min/km. Triathletes were free from any lower limb injuries at the time of testing and must have been back to full training for at least six weeks following any previous injury. All athletes provided fully informed written consent prior to participation. Ethical approval was obtained for all testing procedures from the university ethics committee.

Procedures

A treadmill graded run task was performed without randomization to allow inter-athlete comparisons. Following warm-up and familiarization of 5 min at 6.0 min/km (2.8 m/s), triathletes ran for two minutes each at 5.5, 5.0, 4.5 and 4.0 min/km (3.0, 3.3, 3.7 and 4.2 m/s). A jogging or walking cool down was given. All acceleration and deceleration between running velocity blocks were set to 0.1 m/s^2. Data were collected for the final 20 s of each two minutes block to ensure gait had stabilized following pace change. Athletes were unaware of when recording was taking place. Twelve males (34±5 years, 75.6±6.2 kg, 1.80±0.04 m) repeated the trial after exactly seven days for inter-day reliability analysis.

All triathletes wore spandex shorts or trisuits and their own regular training shoes. Height, weight and bilateral trochanterian height were recorded according to International Society for the Advancement of Kinanthropometry (ISAK) protocols. Retroflective markers (10 mm) were attached to the lower body according to a modified three dimensional (3D) model (Figure 7.1) (280).

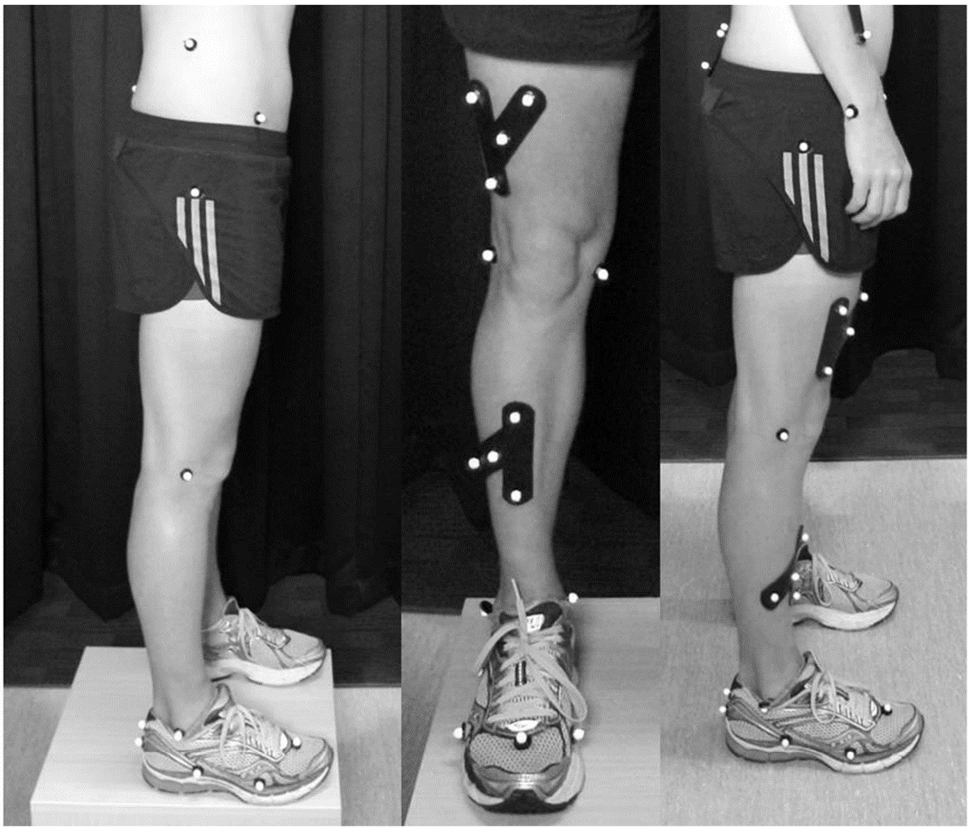

Figure 7.1: Lower body marker locations without and with tracking clusters

Data collection and analysis

A 9-camera VICON motion analysis system (Oxford Metrics Ltd., Oxford, UK) combined with a Bertec instrumented treadmill (BERTEC Corp, Worthington, OH, USA) were used for kinematic (200 Hz) and ground reaction force (1000 Hz) collection, respectively. Functional joint positions were determined using a custom built, MATLAB constrained optimization program (*Optimization Toolbox,* Mathworks Inc.; Natick, MA) detailed by Besier et al. (260). Joint angles and moments were calculated via inverse kinematics using Visual3D software (*Visual3D™,* C-motion, Inc.; Rockville, MD). Anatomical co-ordinate systems were defined according to specifications reported by Besier et al. (260) and Lorimer et al. (280).

Variables were averaged over ten consecutive steps for the left leg for each individual. Horizontal velocity was taken as treadmill velocity and was assumed to be constant. Stiffness values were normalized to body weight before statistical analysis.

Stiffness calculations

Stiffness values were calculated using a custom written Labview program (*Labview,* National Instruments Corp.; Austin, Tx) for the first half of stance, from initial heel contact to maximal vertical ground reaction force for all measures (242). Stiffness calculations were carried out using the equations in Table 7.1.

Table 7.1: Biomechanical stiffness model calculations, variables and equipment

Stiffness calculation	Terms list	Key variables
Vertical stiffness		
$k_{vert/time} = \frac{F_{max}}{\Delta y}$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta y = -\frac{F_{max}}{m}\frac{t_c^2}{\pi^2} + g\frac{t_c^2}{8}$	F_{max} = peak vertical force, Δy = centre of mass displacement, m = subject mass, t_c = contact time, t_f = flight time, g = acceleration due to gravity.	Vertical force (159)
Leg stiffness		
$k_{leg/time} = \frac{F_{max}}{\Delta L}$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta y = -\frac{F_{max}}{m}\frac{t_c^2}{\pi^2} + g\frac{t_c^2}{8}$ $\Delta L = L_0 - \sqrt{L_0^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta y$	F_{max} = peak vertical force, ΔL = change in leg length, Δy = centre of mass displacement, L_0 = trochanterian height, m = subject mass, t_c = contact time, t_f = flight time, g = acceleration due to gravity, *v* = horizontal velocity	Contact time Horizontal velocity Standing leg length (243)
Joint stiffness		
$k_{joint} = \frac{\Delta M}{\Delta \theta}$	ΔM = change in joint moment, Δθ = change in joint angle	Three dimensional force Lower body video for inverse dynamics calculation (240, 244)

Joint stiffness combinations, $k_{sumjoints}$, $k_{hip+knee}$ and $k_{knee+ankle}$ were calculated using equations 1-3.

$$k_{sumjoints} = k_{hip} + k_{knee} + k_{ankle} \quad (1)$$

$$k_{hip+knee} = k_{hip} + k_{knee} \quad (2)$$

$$k_{knee+ankle} = k_{knee} + k_{ankle} \quad (3)$$

Statistical analysis

Descriptive statistics for all variables are presented in Table 7.2 for the test-retest group (n=12) and the complete study sample. Data were assessed for between-trial measurement reliability and measurement variability at the 90% confidence level following log transformation (264). Robustness was maintained by using two criteria each to determine the level of reliability and variability (265).

Measurement reliability was determined to be 'good' when the percent difference between means (MDiff%) was <5% and the effect size (ES) was trivial (0 - 0.2) or small (0.2 - 0.6) (121). If one of these criteria were not met then measurement reliability was interpreted as 'moderate'. 'Poor' reliability resulted in neither criteria being met (265).

Measurement variability was assessed from typical error, reported as coefficient of variation percentage (CV%) (264, 265) and intraclass correlation coefficient (ICC) with upper and lower confidence limits (265). Criteria for 'small' measurement variability were CV <10% and ICC >0.70 (121, 265). If CV was >10% or ICC <0.70 then variability in the measurement was deemed 'moderate'. 'Large' measurement variability was reported if neither criteria for 'small' was met.

For overall reliability all four variables (effect size, percent difference between means, coefficient of variation and interclass correlation) were assessed. 'Good' reliability required all four criteria to be met. 'Moderate' reliability resulted from one criteria outside the limits, with a 'poor' overall reliability recorded for variables with two or more criteria outside the limits (242).

Results

Sixty-six triathletes had viable data at 5.5 min/km, 67 at 5.0 min/km, 64 at 4.5 min/km and 50 at 4.0 min/km. Differences between males and females were trivial therefore data for men and women were combined. The average stiffness for the complete sample tended to be slightly higher than for the test-retest group variability and the general trend of the data were similar between the two groups.

Test-retest reliability for the four different paces are presented in Table 7.3. Overall test-retest reliability remained relatively stable across the pace ranges investigated. Variability in the joint stiffness tended to change the most with pace changes, giving large confidence intervals for the joint measures. Combining the knee and ankle joint stiffness improved the overall reliability compared to the knee stiffness alone.

Table 7.2: Mean (±SD) lower body stiffness with increasing running pace

		Test-retest (n=12)		All triathletes		
Stiffness	Pace (min/km)	Mean	±SD	Mean	±SD	n
$k_{vertical/time}$ (kN/m/kg)	5.5	0.353	0.045	0.371	0.042	68
	5.0	0.361	0.044	0.389	0.047	71
	4.5	0.403	0.049	0.424	0.052	68
	4.0	0.442	0.055	0.476	0.060	53
$k_{leg/time}$ (kN/m/kg)	5.5	0.163	0.028	0.170	0.024	65
	5.0	0.151	0.022	0.165	0.024	68
	4.5	0.157	0.026	0.164	0.024	65
	4.0	0.154	0.026	0.166	0.028	51
$k_{sumjoints}$ (Nm/°/kg)	5.5	0.451	0.089	0.460	0.088	68
	5.0	0.446	0.089	0.474	0.137	71
	4.5	0.494	0.123	0.493	0.100	68
	4.0	0.518	0.136	0.538	0.105	53
$k_{hip+knee}$ (Nm/°/kg)	5.5	0.316	0.082	0.332	0.077	68
	5.0	0.308	0.073	0.339	0.129	71
	4.5	0.344	0.106	0.348	0.082	68
	4.0	0.357	0.122	0.375	0.088	53
$k_{knee+ankle}$ (Nm/°/kg)	5.5	0.252	0.040	0.261	0.061	68
	5.0	0.246	0.050	0.269	0.065	71
	4.5	0.273	0.054	0.290	0.074	68
	4.0	0.293	0.062	0.332	0.081	53
k_{hip} (Nm/°/kg)	5.5	0.199	0.066	0.199	0.060	68
	5.0	0.200	0.054	0.205	0.106	71
	4.5	0.221	0.089	0.203	0.073	68
	4.0	0.225	0.094	0.206	0.069	53
k_{knee} (Nm/°/kg)	5.5	0.117	0.039	0.132	0.052	68
	5.0	0.108	0.047	0.134	0.054	71
	4.5	0.123	0.048	0.145	0.059	68
	4.0	0.132	0.053	0.169	0.068	53
k_{ankle} (Nm/°/kg)	5.5	0.135	0.020	0.128	0.027	68
	5.0	0.138	0.025	0.135	0.030	71
	4.5	0.150	0.028	0.145	0.033	68
	4.0	0.161	0.030	0.163	0.036	53

Table 7.3: Test-retest reliability for twelve triathletes with changing pace

Pace min/km (Velocity m/s)	Reliability		Variability		Overall reliability
	MDiff%	ES	CV% (CL)	ICC (CL)	
5.5 (3.0)	1.4 (-0.9 – 3.8)	-0.13 (-0.15– -0.11)	2.8 (2.1 – 4.7)	0.94 (0.81 – 0.98)	Good
5.0 (3.3)	0.1 (-3.5 – 3.8)	0.01 (-0.02 – 0.03)	5.2 (3.8 – 8.1)	0.85 (0.62 – 0.94)	Good
4.5 (3.7)	0.3 (-1.2 – 1.9)	-0.01 (-0.04 – 0.01)	2.0 (1.5 – 3.2)	0.98 (0.93 – 0.99)	Good
4.0 (4.2)	-0.2 (-2.3 – 1.9)	0.02 (-0.01 – 0.05)	2.9 (2.2 – 4.6)	0.96 (0.88 – 0.98)	Good
$k_{leg/time}$					
5.5 (3.0)	2.4 (-0.3 – 5.2)	-0.19 (-0.20 – -0.18)	3.3 (2.4 – 5.5)	0.96 (0.83 – 0.98)	Good
5.0 (3.3)	0.3 (-1.8 – 2.4)	-0.00 (-0.01 – 0.01)	2.8 (2.0 – 4.4)	0.98 (0.93 – 0.99)	Good
4.5 (3.7)	-2.5 (-4.5 – -0.3)	0.16 0.15 – 0.17)	2.8 (2.1 – 4.6)	0.97 (0.93 – 0.99)	Good
4.0 (4.2)	-2.1 (-4.9 – 0.9)	0.14 (0.13 – 0.16)	3.7 (2.7 – 6.2)	0.96 (0.87 – 0.99)	Good
$k_{sumjoints}$					
5.5 (3.0)	-6.6 (-11.2 – -1.6)	0.39 (0.34 – 0.43)	6.5 (4.7 – 10.9)	0.91 (0.73 – 0.97)	Moderate*
5.0 (3.3)	-5.4 (-10.5 – 0.0)	0.36 (0.32 – 0.40)	7.9 (5.8 – 12.5)	0.86 (0.65 – 0.95)	Moderate*
4.5 (3.7)	-8.2 (-14.5 – -1.5)	0.42 (0.36 – 0.47)	9.6 (7.0 – 15.7)	0.85 (0.62 – 0.95)	Moderate*
4.0 (4.2)	-0.5 (-8.9 – 8.6)	-0.03 (-0.10 – 0.04)	11.3 (8.1 – 19.3)	0.83 (0.55 – 0.94)	Moderate*
$k_{hip+knee}$					
5.5 (3.0)	-10.8 (-18.8 – -2.0)	0.41 (0.37 – 0.45)	12.2 (8.7 – 20.8)	0.84 (0.57 – 0.95)	Poor*
5.0 (3.3)	-5.8 (-11.4 – 0.1)	0.33 (0.29 – 0.37)	8.7 (6.5 – 13.9)	0.88 (0.70 – 0.96)	Moderate*
4.5 (3.7)	-9.4 (-17.0 – -1.1)	0.38 (0.33 – 0.42)	12.1 (8.8 – 19.9)	0.84 (0.60 – 0.94)	Poor*
4.0 (4.2)	-0.6 (-12.1 – 12.3)	-0.07 (-0.13 – -0.01)	16.1 (11.5 – 27.8)	0.79 (0.46 – 0.93)	Moderate*
$k_{knee+ankle}$					
5.5 (3.0)	3.1 (-3.0 – 9.6)	-0.15 (-0.17 – -0.13)	7.7 (5.6 – 13.1)	0.83 (0.55 – 0.94)	Good*
5.0 (3.3)	-3.1 (-8.4 – 2.5)	0.18 (0.16 – 0.20)	8.0 (5.9 – 12.7)	0.87 (0.66 – 0.95)	Good*
4.5 (3.7)	-8.5 (-13.3 – -3.5)	0.45 (0.42 – 0.48)	7.2 (5.3 – 11.7)	0.91 (0.76 – 0.97)	Moderate*
4.0 (4.2)	-4.6 (-10.7 – 2.0)	0.22 (0.18 – 0.26)	8.4 (6.1 – 14.2)	0.90 (0.73 – 0.97)	Good*
k_{hip}					
5.5 (3.0)	-20.5 (-34.3 – -3.9)	0.63 (0.60 – 0.66)	26.2 (18.5 – 46.6)	0.61 (0.13 – 0.86)	Poor
5.0 (3.3)	-7.7 (-14.8 – 0.0)	0.43 (0.41 – 0.46)	11.6 (8.5 – 18.5)	0.83 (0.59 – 0.94)	Poor*
4.5 (3.7)	-7.8 (-19.8 – 5.9)	0.28 (0.25 – 0.31)	19.7 (14.2 – 33.2)	0.68 (0.27 – 0.88)	Poor*
4.0 (4.2)	3.6 (-16.3 – 28.3)	-0.25 (-0.29 – -0.21)	29.8 (20.9 - 53.6)	0.27 (-0.30 – 0.69)	Poor
k_{knee}					
5.5 (3.0)	5.9 (-0.2 – 12.3)	-0.15 (-0.18 – -0.13)	7.4 (5.4 – 12.5)	0.97 (0.90 – 0.99)	Moderate*
5.0 (3.3)	-1.3 (-10.2 – 8.4)	0.02 (0.00 – 0.05)	13.8 (10.1 – 22.1)	0.90 (0.73 – 0.96)	Moderate*
4.5 (3.7)	-10.4 (-19.2 – -0.6)	0.27 (0.25 – 0.30)	14.3 (10.4 – 23.8)	0.91 (0.75 – 0.97)	Poor*
4.0 (4.2)	-8.2 (-18.5 – 3.4)	0.19 (0.16 – 0.22)	15.6 (11.1 – 26.9)	0.91 (0.74 – 0.97)	Poor*
k_{ankle}					
5.5 (3.0)	1.1 (-7.5 – 10.4)	0.01 (-0.00 – 0.02)	11.4 (8.2 – 19.4)	0.55 (0.03 – 0.83)	Poor*
5.0 (3.3)	-4.2 (-10.2 – 2.3)	0.31 (0.30 – 0.33)	9.3 (6.9 – 14.8)	0.75 (0.42 – 0.90)	Good*
4.5 (3.7)	-5.9 (-12.4 – 1.1)	0.41 (0.39 – 0.42)	9.7 (7.1 – 15.9)	0.77 (0.45 – 0.92)	Moderate*
4.0 (4.2)	-1.7 (-8.5 – 5.7)	0.11 (0.10 – 0.13)	9.2 (6.6 – 15.5)	0.84 (0.57 – 0.95)	Good*

** confidence intervals of one or more of the statistics span at least two criteria levels.*

Average within-athlete variation (a) and between-athlete variation (b), as coefficient of variation (CV%), at the different paces, are presented in Figure 7.2. Vertical and leg stiffness showed the lowest variability both within and between athletes and were consistent for all running paces tested. Ankle stiffness variability was lowest of the three joints, both within and between athletes. The hip had the highest variability within athletes however the knee had greater between-athlete variability. The pattern of variability with increasing pace was also different for within-athlete analysis compared to between. Within-athlete variability for the knee, ankle and combined knee and ankle increased with increasing running pace, showing a greater increase in variability as the pace increased. Between-athlete variability for these joints showed a small increase in variability which then appears to decline again as running pace picks up. Hip variability showed a unique sigmoidal pattern both within and between athletes. Interestingly, while combined knee and ankle within-athlete variability sits approximately half way between the two individual joints, for between-athlete variability it is much closer to the individual ankle than the knee.

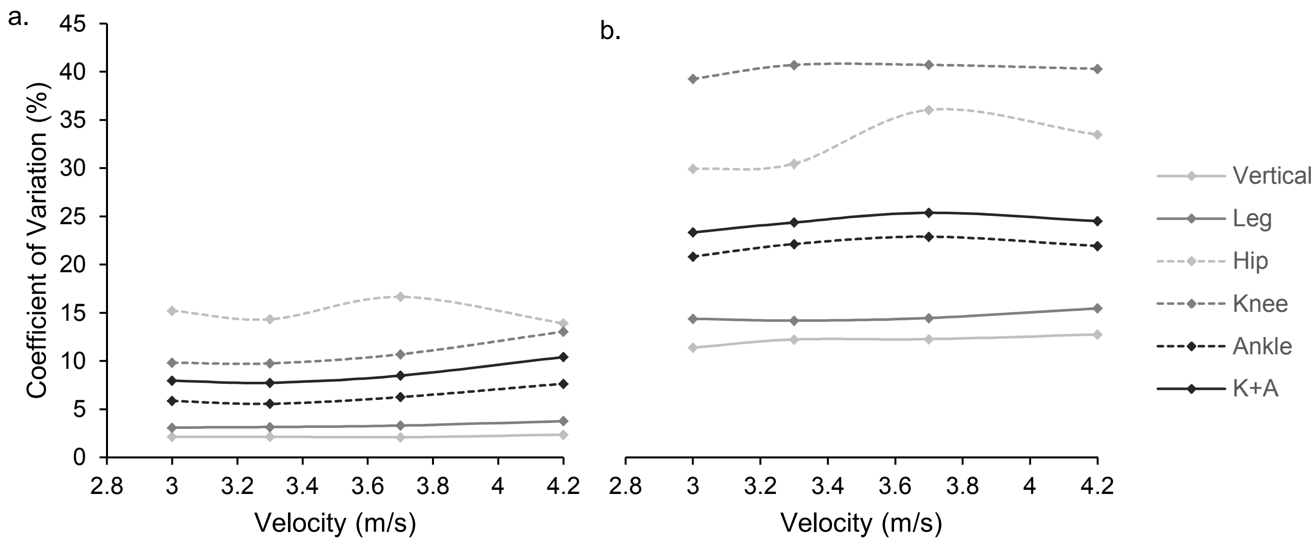

Figure 7.2: a). average within-athlete lower body stiffness variability with increasing pace, b). between-athlete lower body stiffness variability with increasing pace

Plots of the within-athlete variability distribution for each of the individual joints reveals further details (Figure 7.3). Not only did the magnitude of the variability increase moving proximally, but the range of step-to-step variability within the sample group also increased. Ankle stiffness variability was fairly consistent with increasing running pace however variability did increase for the fastest pace (4.0 min/km). Knee variability was also stable for the first three paces with the majority of athletes showed an increase in variability for the fastest pace. In contrast, hip stiffness variability appeared to decrease for approximately half the group at the fastest pace. A small number of athletes showed very large within-athlete hip stiffness variability for the 5.5 and 4.5 min/km pace which appears to be the main contributor to the sigmoidal pattern observed in Figure 7.2 (a).

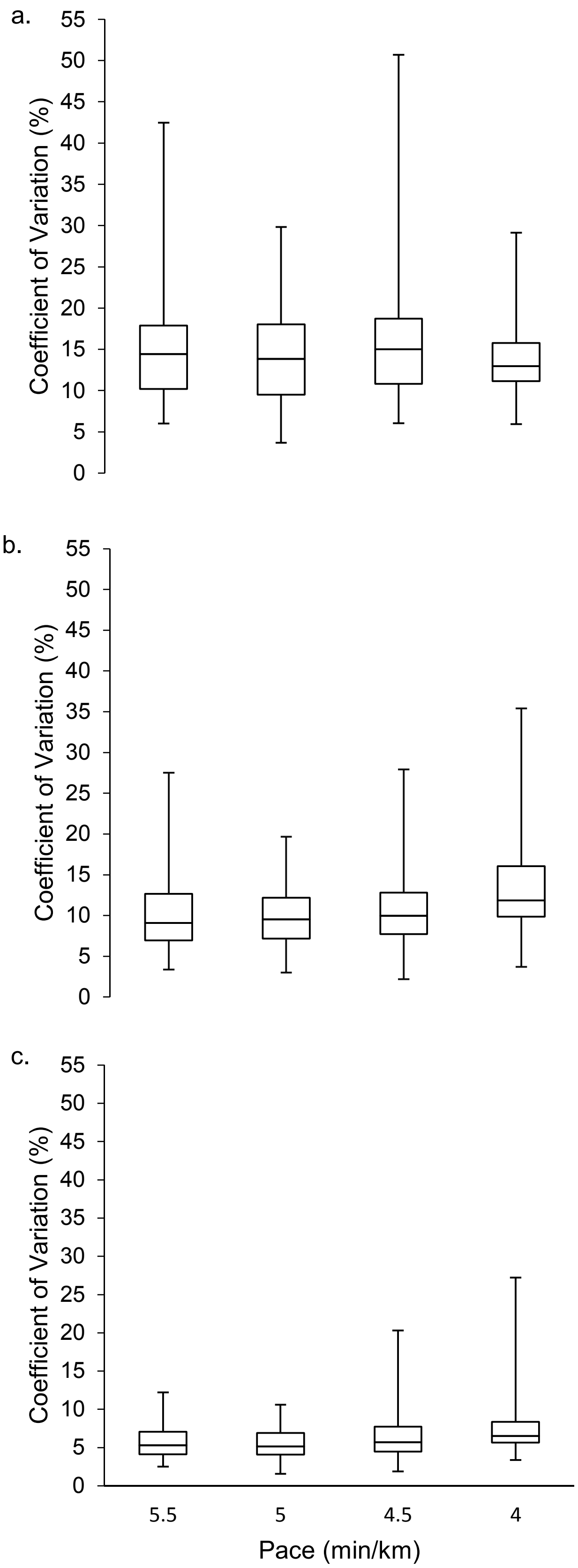

Figure 7.3: Hip a). knee b). and ankle c). within-athlete coefficient of variation with increasing running pace.

Discussion

The insidious nature of overuse injuries suggests that any differences in movement between at-risk athletes and athletes not at-risk will be small. A measure that shows good reliability from one test to the next is therefore of great importance to allow changes to be noticeable. For any measure that is specific to the sporting activity of the athlete, reliability over a wide range of performance levels is also important to allow tailoring of the screening to the requirements of the athlete. Vertical and leg stiffness would make useful screening measures as they showed no change in overall reliability within the range of paces tested. As individual measures, joint stiffness reliability varied with pace and no single pace could be identified where the reliability of each of the joints was ideal. Combining the joints using equations 1-3 improved the overall reliability of the stiffness measures compared to the individual joint stiffness. Joint combinations, particularly combined knee and ankle stiffness ($k_{knee+ankle}$), provide greater reliability of measurement. The contributions of each joint can then be investigated further in order to gain further information about the movement control of the athlete.

When studying movement control, the more focused the measurement the more variability we can expect. The difference between coordinative variability and endpoint variability (79) are well highlighted when examining the coefficients of variation (CV%) of the individual joints compared to leg or vertical stiffness. Both the within-athlete variability and between-athlete variability are lowest for the endpoint movement measures (vertical and leg) than for the component movements (joints). In order to achieve stable running on a treadmill at a fixed pace, the endpoint goal of the movement is similar. Variation in optimal stiffness between athletes can be accounted for with differences in leg length and muscular strength and power, resulting in greater between-athlete variability observed for all measures compared to within-athlete variability. A complex interaction between visual, vestibular and proprioceptive inputs result in fine tuning coordinated muscle activity leading to the small amounts of variability from step to step.

Compression of the 'leg spring' is achieved through coordinated rotation of the leg joints. Winter (274) reported that variability of the joints increased moving up the kinetic chain. The ankle responds directly to the applied force and supports the lower leg. The knee and hip on the other hand have more influence over fine tuning the movement and are able to provide compensation for the other joints (274). This concept is supported for joint stiffness with the within-athlete variability increasing moving proximally (Figure 7.2, a). For between-athlete variability however, the knee had the greatest variability. A high between-athlete variability suggests that different knee stiffness strategies are used by different athletes to achieve the same running pace. This supports the observation that the knee provides the greatest contribution to leg stiffness during running (280). Located in the middle and with a greater range of motion than the ankle joint, the knee controls to a large extent the compression of the 'leg spring' and therefore its stiffness. Connected to both the hip and ankle joint through biarticular muscles the knee is the route by which forces are distributed up the kinetic chain (285). Through the interactions of reciprocal inhibition, passive insufficiency and active insufficiency the knee influences the force production capacity of the gastrocnemius and therefore the balance of force directed through the Achilles tendon via the triceps surae muscle complex. With such an influential role in determining stable running mechanics, it is understandable that the knee exhibits the greatest between-athlete variability.

In modelling studies, first with a single segment leg (171) and then with a two segment leg connected by a knee joint (266), regions of self-stable running based on the angle of attack were identified that were enlarged with increasing velocity. An upper limit to velocity was present which could not be exceeded without increasing the stiffness of the knee joint (266). For the single segment leg, increasing horizontal velocity allowed for self-stable running with greater variability in the stiffness and angle of attack parameters (171). Both the single segment and two-segment legs produced bands of self-stable running. A three segment leg is likely to follow a similar trend. Greater tolerance to variation to support stable running at a given running pace, explains the increasing within-athlete variability of the knee and ankle with increasing running pace (Figure 7.2, a). Between-athlete variability however was relatively stable for all running paces with only a small initial increase for both the knee and ankle. Comparison between actual running data and the two segment model showed that humans tended to prefer low values of knee stiffness for the given velocity and angle of attack (266). Therefore, for each pace change all athletes appear to modify stiffness by a similar degree to maintain these low values. Identifying outliers from this general trend of stiffness adjustment with pace may provide a method of identifying individuals at greater risk of developing injury.

While good repeatability from one day to another is required to pick up small differences in stiffness measurements, it has been suggested that a high step-to-step variability may be protective against overuse injuries. The current theory for overuse injuries is that tissue damage from continual loading out paces tissue repair mechanisms (293). Greater variability in tissue loading from one step to another would reduce the cumulative load on that tissue or area of tissue where loading is highest. In the study of tendinopathy, the theory of stress shielding has been proposed where reducing the load to the tendon tissue brings about the same biochemical changes as seen in advanced tendinopathic tissue (61, 63). High variability would also be protective against tissue degeneration, from reduced loading, by ensuring that all tissues are being loaded equally. Joint stiffness gives an indication of the movement patterns occurring at each joint during the loading phase of stance. Healthy variability at a joint during steady paced treadmill running is the collective result of available range of motion, coordination between the joints indicative of skill, available muscle strength and power and anthropometric factors. Variability could also be introduced through acute muscle fatigue or changing the constraints of the task.

In terms of Achilles tendon injury risk, the ankle and knee are likely to have the greatest impact with the muscles of the tendon directly controlling movement of these two joints. Step-to-step variability for both the knee and ankle were relatively consistent for the majority of athletes but increased for the final pace (4.0 min/km) (Figure 7.3, b & c). A small number of athletes showed much greater increases in step to step variability for the final two paces (4.5 and 4.0 min/km). Knee stiffness variability was lowest at the 5.0 min/km pace, producing a slight 'U-shape' trend. During treadmill running with stride rate manipulation, the lowest energy cost occurs at around preferred stride rate (206). The low oxygen cost of running suggests that muscular effort is small and maintenance of a dynamic 'bouncing' gait is predicted with little fluctuation in control. Variability in walking gait has been shown to be high in both young children and the elderly as well as individuals with neurological disorders (294). It is therefore hypothesised that the preferred pace is the pace at which the lowest stiffness variability is observed (i.e. 5.0 min/km) with greater increases in variability occurring as the pace becomes more uncomfortable (i.e. 4.0 min/km). In contrast, detrended fluctuation analysis of running gait showed a 'U-shaped' trend with the lowest long range correlation for the preferred pace, suggesting a greater adaptability to changes in task and environment constraints at this pace (295). In the current research however, only 10 steps were considered. Scatter around the correlation line increases as the number of steps considered increases (295), therefore correlation between the 10 steps analysed are likely to be high. In order to reduce the risk of injury, athletes should be encouraged to utilise a large range of paces during training in order to facilitate higher step-to-step variability. Paces at both faster and slower than preferred pace appear to increase variability at the knee and to a smaller extent at the ankle. Training with a limited pace range has been shown to increase the risk of Achilles tendon injury (126).

Some athlete's experienced very large increases in ankle stiffness variability for the final two paces (4.5 and 4.0 min/km). Acute muscle fatigue or reduced coordination may cause heavier landing or reduced ankle control prior to contact increasing the variability of the movement patterns (296, 297). Alternatively the constant movement of the treadmill belt could force an athlete to move their legs at a rate faster than they control when running outside of their comfort range. While all athletes were well-trained and running speeds were selected to match the range of speeds encountered in training and racing, running for two minutes at the final pace may have been at the limits of some of the athlete's capabilities. There may be a point at which variability becomes detrimental and individual steps land outside of the physiological range of the tissue, increasing the risk of sustaining microtrauma that can progress into overuse injuries. Therefore, use of extreme fast pace and treadmill controlled fast paces should be used with caution.

The hip showed an interesting fluctuation in variability with variability tending to be lower at 5.0 min/km and lowest at 4.0 min/km compared to the 5.5 and 4.5 min/km paces. Analysis of changes in hip stiffness with increasing running pace showed trivial changes (292). From the leg stiffness model, the hip along with the knee controls the angle of contact and therefore influences the stride length and the centre of mass trajectory during stance (159, 170). The angle of contact is initiated prior to contact therefore hip stiffness during stance is not greatly altered. Hip stiffness variability however may be influenced by the stride length. During walking an increase in stride length results in decreased stride length and frequency variability (298). It is possible that the decreases in hip stiffness variability coincides with increases in stride length in order to achieve the new pace. Increasing pace from 5.5 to 5.0 min/km resulted in a small reduction in leg stiffness (292) supporting a change in stride length to achieve the new running pace. Gluteus maximus activity and hip extensor moments tended to increase with increasing running speed (299), propelling the COM forward. Increased activity should reduce the available variability at the hip, however for increases in pace that are driven by increased stride rate, the hip takes on a more supportive role leading to increases in the variability. Hip stiffness variability would fluctuate but become progressively smaller as running pace increases.

Conclusions

Reliability remained stable over a range of paces, which potentially allows screening of athletes to be adapted to the individual demands of the athlete. Vertical, leg knee and ankle between-athlete stiffness remained relatively consistent with increasing pace. Athletes who do not follow the same trends in stiffness change may be at greater risk of injury. The individual knee and ankle joints showed slight 'U-shaped' patterns of within-athlete variability. It is hypothesised that lowest variability is achieved at the pace closest to preferred running pace. Athletes should therefore be encouraged to utilise a wide variety of paces during training in order to increase the step-to-step variability in order to prevent tissue overload and progressive injury.

CHAPTER 8

INFLUENCE OF PRIOR CYCLING ON LOWER LIMB STIFFNESS IN TRIATHLETES

This chapter comprises the following paper:

Lorimer, A., Hume, P., Pearson, S. Influence of prior cycling on lower limb stiffness in triathletes**.** To be submitted to *Sports Biomechanics*.

Overview

Background: Triathletes report a feeling of loss of coordination and discomfort during the initial stages of running following cycling. It is widely thought that this period of uncomfortable running could have increased risk of injury.

Aim: To quantify the magnitude of vertical, leg and joint stiffness changes during running following a 30 minute athlete controlled cycle.

Methods: Thirty-four professional or top level age group triathletes (22 male; 12 female) participated. Athletes performed a graded isolated run (IR) at 5.5, 5.0, 4.5 and 4.0 min/km. Changes in stiffness were assessed between the IR and a steady pace transition run (TR) following a 30 minute cycle.

Results: Vertical (ES=0.59; 90% CI -0.21-2.22), leg (0.63; -0.27-3.88) and ankle (0.55; -0.13-1.98) showed possible small increases in stiffness in the first minute of TR compared to IR. Scatter plot analysis showed the majority of athletes demonstrated very little change in stiffness, however a small number responded with increased leg and vertical stiffness. Joint stiffness changes showed greater scatter with two different responses noted, either an increase in knee and ankle stiffness or an increase in ankle stiffness and a decrease in knee stiffness.

Discussion: The majority of athletes appeared to show little change in running movement patterns following 30 minutes of cycling, however individual responses were present within the group. An increase in vertical, leg, knee and ankle stiffness is consistent with increased flight time and decreased contact time. Increases in flight time without changes in stride length could explain the increased cost of running following cycling with energy wasted in producing unnecessary vertical propulsion. A small number of athletes responded with decreased knee stiffness but increased ankle stiffness which could indicate an uncoupling of normal gait coordination and may increase the risk of Achilles tendon injury due to enhanced shearing or uneven torsional load within the tendon. Further research is required looking at the relationship between the different gait parameters, running economy and the stiffness changes in responding and non-responding athletes in order to gain a better understanding of how gait is changed in responding athletes.

Conclusion: Gait mechanics, as measured through lower body stiffness, are largely unaffected in most well-trained triathletes following 30 minutes of self-paced cycling. However, a small number of athletes respond to running after cycling with modified movement patterns which may be detrimental to performance and increase injury risk.

Introduction

Triathlon offers a unique challenge from both a performance and injury perspective in that athletes are required to rapidly change from one discipline to another during racing. Running time in the triathlon has been highly, positively correlated (r = 0.97) with overall triathlon performance (300). However, the running segment appears to be the most challenging or difficult segment to complete (300, 301). The bicycle to run transition seems to be more dramatic and difficult than the earlier swim to bike transition. Triathletes report a feeling of loss of coordination and discomfort during the initial stages of running following cycling (224, 230).

Running ability has become increasingly important due to regulations introduced in 1995 by the International Triathlon Union allowing drafting in the cycle segment of elite Olympic distance races (302). The elimination of the drafting rule has allowed pack cycling in elite triathlons, resulting in groups of triathletes entering the bicycle to run transition simultaneously. Even in non-drafting races, the ability to run well following hard cycling is key in determining the outcome. It is therefore the athlete who can adopt their optimal running pattern as quickly as possible off the bike that has an advantage.

Running economy has been shown to decrease in triathletes of all levels following cycling when compared to an isolated run or following a fatiguing run protocol (224, 226, 303-306). However, others have reported no change to running economy in elite triathletes (307) or changes in only some of the athletes (225). Possible reasons for an increase in the cost of running following cycling have been proposed as fatigue, muscle activity changes and kinematic changes (308). Researchers have tried to account for the effect of fatigue with comparisons to changes in running physiology and biomechanics following a fatiguing run (309).

Changes in running biomechanics off the bike have primarily focused on stride rate and stride length, with no change following various cycling protocols reported by some authors (207, 303, 308, 310). Smaller stride length and faster stride rate following cycling have also been reported (92, 311, 312). Stride length is significantly and positively correlated with run performance in triathlon, with those who can maintain longer stride length achieving higher finishing positions (313). Changes in lower limb joint angles (225, 228, 314) and pelvis and spine in the sagittal plane (228) have been reported following cycling compared to isolated running. Ability to maintain postural stability after prolonged exercise in triathletes has also been shown to be impaired (232). Not all triathletes exhibited changes in joint kinematics which may account for the variation in results reported in the literature (225). This was also the case when considering changes in muscle activity (225, 230, 314). In terms of time-course, kinematic changes have been observed to be significant for the first 1200 m of running after a

45 min cycle (314) and for at least 14 minutes following 30 minutes of cycling (228). Adaptation to proprioceptive, vestibular and visual inputs were suggested to explain a temporary delay in postural control feedback mechanisms (232). However, muscle fatigue and cardiovascular redistribution cannot be ruled out and may exacerbate the impairment (232).

While evidence is lacking, it is widely thought that the period of altered feeling and/or running mechanics following cycling is associated with an increased risk of running injury (228). To our knowledge, only one study has looked directly at altered running mechanics and injury. Chapman et al. (229) compared running mechanics of 10 triathletes who had experienced exercise related leg pain with 24 matched controls. While knee and ankle joint kinematics were unchanged, changes in muscle recruitment were calculated to have a relative risk ratio of 2.62 (1.34-6.01) when defined by muscle (229).

Achilles tendon injuries are problematic in triathletes with a prevalence of up to 50% in Olympic distance athletes (16, 161). Classified as the most severe lower limb injury based on the number of training days lost (16), being able to identify at risk athletes and introduce preventative measures is of current concern. As a measure that is modified by multiple risk factors for Achilles tendon injuries, stiffness may provide a useful method for evaluating injury risk (167, 279). Changes in vertical and leg stiffness are associated with altered displacement in the centre of mass (159). Centre of mass displacement was found to change by at least 4% in elite and middle level triathletes, during the braking phase of stance following an exhaustive stepped cycling protocol (226). The angle of attack (leg angle with respect to the ground) may also be altered in running following cycling contributing to altered leg and joint stiffness (92). Leg stiffness but not vertical stiffness was significantly higher following a 30 minute intensity controlled cycle compared to an isolated run (214). This resulted from decreased contact time, increased vertical force and decreased change in leg length (214). Effect sizes for both leg and vertical stiffness were small and unclear (279). During the World Championship race in Beijing 2008, estimates of vertical and leg stiffness from temporal parameters showed that speed, vertical stiffness and leg stiffness decreased from the beginning of lap one to four but increased to equivalent of lap one for the finish (211). Therefore it seems that vertical and leg stiffness are altered in triathletes during the run and that initial stiffness when running off the bike is possibly altered compared to fresh running. Whether stiffness is changed when the athlete controls the cycling intensity remains unclear. How the lower limb joints alter their stiffness in order to achieve stable running under cycle to run transition conditions has not yet been investigated.

Aim

The study aimed to quantify the magnitude of vertical, leg and joint stiffness changes during running following a 30 minute athlete controlled cycle.

Methods

Athlete characteristics

Thirty-four triathletes (22 male; 34±9 years, 76.1 ±6.7 kg, 1.80 ±0.05 m and 12 female; 33±7 years, 59.4 ±5.9 kg, 1.68 ±0.07 m) volunteered for the research. All athletes were currently competitive as professional or top level age group Olympic distance and long distance triathletes. A personal best time in the previous season of 2h 20 min/ 2h 40 min (male/female) for Olympic distance or 10 h/ 11h 30 min (male/female) for Iron distance and the ability to run for over two minutes at 4.0 min/km was required. Triathletes were free from lower limb injuries at the beginning of the study and had been back to full training for at least six weeks following any previous injury. All athletes provided fully informed written consent prior to participation. Ethical approval was obtained for all testing procedures from the university ethics committee.

Procedures

Following warm-up and familiarization of five minutes at 6.0 min/km (2.8 m/s), triathletes completed a graded run task (IR) comprised of two minute run blocks at 5.5, 5.0, 4.5 and 4.0 min/km (3.0, 3.3, 3.7 and 4.2 m/s). A jogging or walking cool down was given at the end of the graded run task. All accelerations and decelerations were set to 0.1 m/s^2. Data were collected for the final 20 s of each two minute block in order to ensure gait had stabilized following pace change. Based on the training status of the triathletes this run protocol was considered to be non-fatiguing.

Following a break of at least five minutes, triathletes cycled for 30 minutes on a Minoura M70 Magturbo windtrainer (Minoura Co., Ltd, Anpachi, Japan) using their own bike. Instructions were to cycle at an intensity similar to a sprint distance triathlon, and to follow any specific individual transition protocols such as increasing cadence or stretching in the final two minutes. Athletes were informed of time at 10, 15, 20, 25 and 29 minutes and were given a 30 second count down to the finish. In the last five minutes of the cycle, triathletes were asked what pace they wished to complete the 20 minute transition run (TR) at, 5.0, 4.5 or 4.0 min/km. A one minute standardised transition was given for athletes to change their shoes. Acceleration was 0.2 m/s^2 in order to reach desired pace within the first 30 seconds. Athletes ran at their selected pace for up to 20 minutes. Data were recorded for the last 10 seconds of each minute for the first 10 minutes then every two minutes. Athletes were unaware of when recording was taking place.

All triathletes wore spandex shorts or tri-suits and their own regular training shoes. Height, weight and bilateral trochanterian height were recorded according to International Society for the Advancement of Kinanthropometry (ISAK) protocols. Retroflective markers (10 mm) were attached to the lower body according to a modified three dimensional (3D) model (Figure 8.1)(280). Following a static standing calibration, femoral condyl and malleoli markers were removed. For dynamic calibration of the hip joint, participants moved first the right then the left leg through a combination of flexion, abduction, adduction and extension (260, 263). Knee joint centre dynamic calibration involved three shallow squat movements (260).

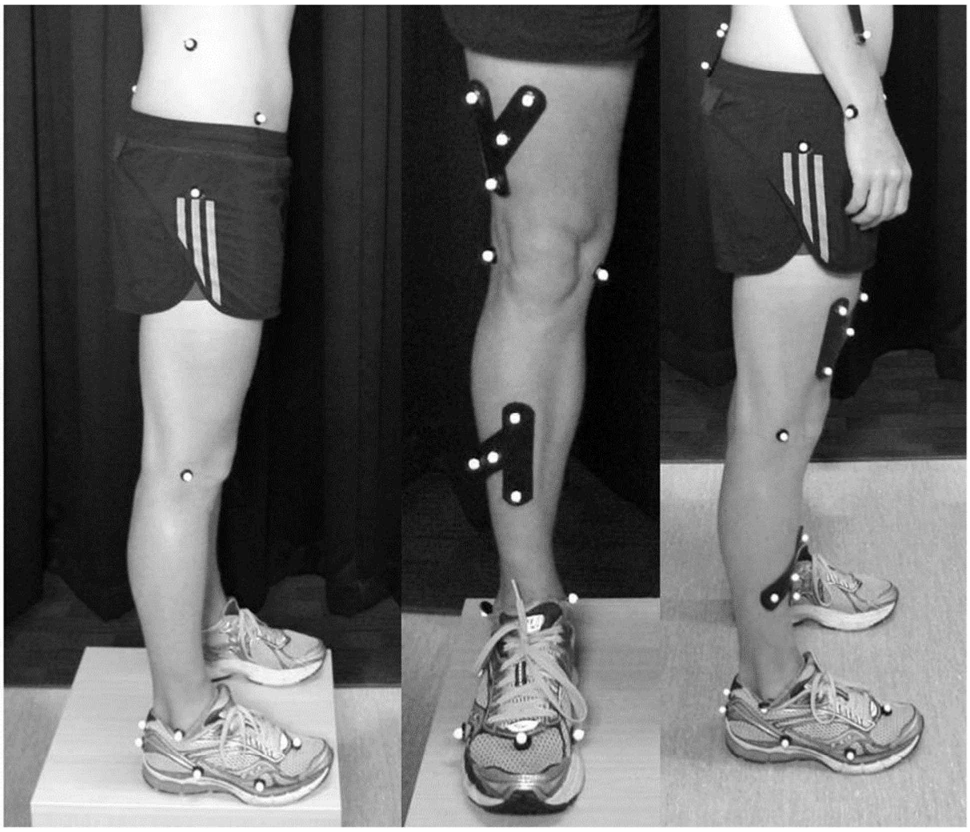

Figure 8.1: Lower body marker locations without and with tracking clusters

Data collection and analysis

A 9-camera VICON motion analysis system (Oxford Metrics Ltd., Oxford, UK) combined with a Bertec instrumented treadmill (BERTEC Corp, Worthington, OH, USA) were used for kinematic (200 Hz) and ground reaction force (1000 Hz) collection, respectively. Functional joint positions were determined using a custom built, MATLAB constrained optimization program (*Optimization Toolbox,* Mathworks Inc.; Natick, MA) detailed by Besier et al. (260). Joint angles and moments were calculated via inverse kinematics using Visual3D software (*Visual3D™,* C-motion, Inc.; Rockville, MD). Anatomical co-ordinate systems were defined according to specifications reported by Besier et al. (260) and Lorimer et al. (280).

Variables were averaged over ten steps per leg for each individual. Horizontal velocity was taken as treadmill velocity and was assumed to be constant. Vertical, leg and joint stiffness during running were assessed to measure changes following cycling. Stiffness values were normalized to body weight before statistical analysis.

Stiffness calculations

Stiffness values were calculated using a custom written Labview program (*Labview,* National Instruments Corp.; Austin, TX). Stiffness was calculated for the first half of stance from initial ground contact to maximal vertical ground reaction force for all stiffness measures (242). Stiffness calculations were carried out using the equations in Table 8.1.

Table 8.1: Biomechanical stiffness model calculations, variables and equipment

Stiffness calculation	Terms list	Key variables
Vertical stiffness		
$k_{vert/time} = \frac{F_{max}}{\Delta y}$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta y = -\frac{F_{max}}{m}\frac{t_c^2}{\pi^2} + g\frac{t_c^2}{8}$	F_{max} = peak vertical force, Δy = centre of mass displacement, m = subject mass, t_c = contact time, t_f = flight time, g = acceleration due to gravity.	Contact time (243)
Leg stiffness		
$k_{leg/time} = \frac{F_{max}}{\Delta L}$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta y = -\frac{F_{max}}{m}\frac{t_c^2}{\pi^2} + g\frac{t_c^2}{8}$ $\Delta L = L_0 - \sqrt{L_0^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta y$	F_{max} = peak vertical force, ΔL = change in leg length, Δy = centre of mass displacement, L_0 = trochanterian height, m = subject mass, t_c = contact time, t_f = flight time, g = acceleration due to gravity, *v* = horizontal velocity	Contact time Horizontal velocity Standing leg length (243)
Joint stiffness		
$k_{joint} = \frac{\Delta M}{\Delta \theta}$	ΔM = change in joint moment, Δθ = change in joint angle	Three dimensional force Lower body video for inverse dynamics calculation (240, 244)

Joint stiffness combinations, $k_{sumjoints}$, $k_{hip+knee}$ and $k_{knee+ankle}$ were calculated using equations 1-3.

$$k_{sumjoints} = k_{hip} + k_{knee} + k_{ankle} \quad (1)$$

$$k_{hip+knee} = k_{hip} + k_{knee} \quad (2)$$

$$k_{knee+ankle} = k_{knee} + k_{ankle} \quad (3)$$

Statistical analysis

Descriptive statistics for all variables were calculated as least squares mean to account for missing data points. Differences in stiffness between transition-run (TR) and same paced isolated run (IR), were assessed using Proc Mixed in SAS. The least squares mean (LS mean), percent differences of least squares mean (LS mean % diff), effect sizes (ES), random effects expressed as coefficients of variation (CV %) and 90% confidence intervals were extracted. Effect sizes for stiffness during TR compared to the IR were calculated from the least squares mean difference and the IR standard deviation (121). Effect size thresholds for trivial, small, moderate and large effects were 0.2, 0.6, 1.2 and 2.0 (121). A positive effect sizes indicate an increase in stiffness for TR compared to IR.

Results

The transition run was completed by 12 athletes at 5.0 min/km, 18 athletes at 4.5 min/km and four athletes at 4.0 min/km. Average stiffness for the IR and TR, as an average of all paces are presented in Table 8.2.

Table 8.2: Average stiffness for isolated run and selected times during a transition run in triathletes

	LS mean (90% CI)						
Time (min)	IR	1	2	3	4	5	10
$k_{vertical/time}$ kN/m/kg	0.43 (0.40:0.47)	0.48 (0.43:0.55)	0.45 (0.42:0.48)	0.42 (0.39:0.46)	0.42 (0.39:0.46)	0.43 (0.40:0.47)	0.41 (0.37:0.45)
$k_{leg/time}$ kN/m/kg	0.17 (0.15:0.18)	0.18 (0.16:0.22)	0.17 (0.15:0.19)	0.16 (0.15:0.18)	0.16 (0.15:0.18)	0.16 (0.14:0.18)	0.16 (0.14:0.19)
$k_{sumjoints}$ Nm/°/kg	0.50 (0.45:0.57)	0.52 (0.45:0.60)	0.51 (0.45:0.58)	0.52 (0.45:0.59)	0.50 (0.43:0.58)	0.50 (0.44:0.58)	0.53 (0.46:0.63)
$k_{hip+knee}$ Nm/°/kg	0.36 (0.31:0.41)	0.35 (0.30:0.42)	0.35 (0.31:0.41)	0.36 (0.31:0.43)	0.35 (0.29:0.41)	0.35 (0.30:0.42)	0.38 (0.32:0.47)
$k_{knee+ankle}$ Nm/°/kg	0.29 (0.26:0.33)	0.32 (0.28:0.37)	0.30 (0.27:0.34)	0.29 (0.26:0.33)	0.29 (0.25:0.33)	0.28 (0.24:0.32)	0.29 (0.25:0.33)
k_{hip} Nm/°/kg	0.20 (0.17:0.25)	0.19 (0.15:0.23)	0.20 (0.17:0.25)	0.22 (0.18:0.27)	0.21 (0.17:0.27)	0.22 (0.18:0.28)	0.24 (0.19:0.32)
k_{knee} Nm/°/kg	0.15 (0.12:0.17)	0.16 (0.13:0.19)	0.14 (0.12:0.17)	0.14 (0.11:0.16)	0.13 (0.11:0.16)	0.13 (0.11:0.15)	0.14 (0.11:0.17)
k_{ankle} Nm/°/kg	0.14 (0.13:0.16)	0.16 (0.14:0.18)	0.15 (0.14:0.17)	0.15 (0.13:0.17)	0.15 (0.14:0.17)	0.15 (0.13:0.17)	0.15 (0.13:0.17)

Differences in lower body stiffness during running following a 30 minute self-paced cycle compared to the isolated run condition are presented as percent difference of the least squares mean (LS mean diff. %) and effect sizes in Table 8.3. Non-trivial effect sizes are shaded according to magnitude of the effect.

Table 8.3: Magnitude of change in lower body stiffness measures during a transition run compared to isolated running in triathletes

	IR LS mean (Lower: Upper CI)	LS mean (Lower:Upper CI) LS mean % diff. compared to IR ES compared to IR (Lower:Upper CI)					
Time (min)	0	1	2	3	4	5	10
$k_{vertical/time}$	0.43	0.48	0.45	0.42	0.42	0.43	0.41
	(0.40:0.47)	(0.43:0.55)	(0.42:0.48)	(0.39:0.46)	(0.39:0.46)	(0.40:0.47)	(0.37:0.45)
		0.59	0.21	-0.16	-0.16	-0.05	-0.37
		(2.22:-0.21)	(1.30:-0.25)	(0.81:-0.46)	(0.89:-0.47)	(0.99:-0.40)	(0.59:-0.59)
$k_{leg/time}$	0.17	0.18	0.17	0.16	0.16	0.16	0.16
	(0.15:0.18)	(0.16:0.22)	(0.15:0.19)	(0.15:0.18)	(0.15:0.18)	(0.14:0.18)	(0.14:0.19)
		0.63	0.18	-0.07	-0.08	-0.13	-0.25
		(2.88:-0.27)	(1.77:-0.35)	(1.47:-0.45)	(1.44:-0.43)	(1.40:-0.48)	(1.52:-0.62)
$k_{sumjoints}$	0.50	0.52	0.51	0.52	0.50	0.50	0.53
	(0.45:0.57)	(0.45:0.60)	(0.45:0.58)	(0.45:0.59)	(0.43:0.58)	(0.44:0.58)	(0.46:0.63)
		0.17	0.24	0.23	0.10	0.14	0.43
		(1.73:-0.10)	(1.68:-0.02)	(1.72:-0.05)	(1.64:-0.13)	(1.61:-0.10)	(2.16:-0.02)
$k_{hip+knee}$	0.36	0.35	0.35	0.36	0.35	0.35	0.38
	(0.31:0.41)	(0.30:0.42)	(0.31:0.41)	(0.31:0.43)	(0.29:0.41)	(0.30:0.42)	(0.32:0.47)
		-0.09	-0.06	0.05	-0.18	-0.07	0.32
		(1.52:-0.55)	(1.39:-0.52)	(1.64:-0.49)	(1.41:-0.62)	(1.48:-0.56)	(2.23:-0.44)
$k_{knee+ankle}$	0.29	0.32	0.30	0.29	0.29	0.28	0.29
	(0.26:0.33)	(0.28:0.37)	(0.27:0.34)	(0.26:0.33)	(0.25:0.33)	(0.24:0.32)	(0.25:0.33)
		0.39	0.08	-0.04	-0.06	-0.24	-0.10
		(1.65:-0.19)	(1.10:-0.33)	(0.96:-0.38)	(0.99:-0.40)	(0.68:-0.49)	(0.98:-0.47)
k_{hip}	0.20	0.19	0.20	0.22	0.21	0.22	0.24
	(0.17:0.25)	(0.15:0.23)	(0.17:0.25)	(0.18:0.27)	(0.17:0.27)	(0.18:0.28)	(0.19:0.32)
		-0.49	0.01	0.25	-0.02	0.29	0.63
		(1.25:-0.86)	(1.78:-0.58)	(2.26:-0.52)	(2.01:-0.68)	(2.33:-0.50)	(3.03:-0.41)
k_{knee}	0.15	0.16	0.14	0.14	0.13	0.13	0.14
	(0.12:0.17)	(0.13:0.19)	(0.12:0.17)	(0.11:0.16)	(0.11:0.16)	(0.11:0.15)	(0.11:0.17)
		0.19	-0.11	-0.23	-0.29	-0.38	-0.19
		(1.38:-0.31)	(0.82:-0.42)	(0.68:-0.49)	(0.64:-0.52)	(0.47:-0.58)	(0.85:-0.52)
k_{ankle}	0.14	0.16	0.15	0.15	0.15	0.15	0.15
	(0.13:0.16)	(0.14:0.18)	(0.14:0.17)	(0.13:0.17)	(0.14:0.17)	(0.13:0.17)	(0.13:0.17)
		0.55	0.37	0.26	0.34	0.12	0.12
		(1.98:-0.13)	(1.61:-0.20)	(1.48:-0.25)	(1.67:-0.23)	(1.27:-0.32)	(1.38:-0.38)

Shading indicates the magnitude of the effect size increasing in shade for small and moderate effects.

Changes in stiffness following cycling were generally small or trivial in magnitude with large confidence intervals. There were possible small increases in vertical and leg stiffness during the first 1-2 minutes following cycling. Ankle stiffness showed possible, small increases in stiffness for the first four minutes of running following cycling. The knee did not show any changes in stiffness until after the second minute of running off the bike. Hip stiffness changes were variable with a decrease in stiffness after the first minute followed by either no change or a small increase in stiffness in the subsequent minutes of running. Combined knee and ankle showed a possible small increase in stiffness for the first minute of running but then tended towards trivial or small decreases in stiffness for the remainder of the run.

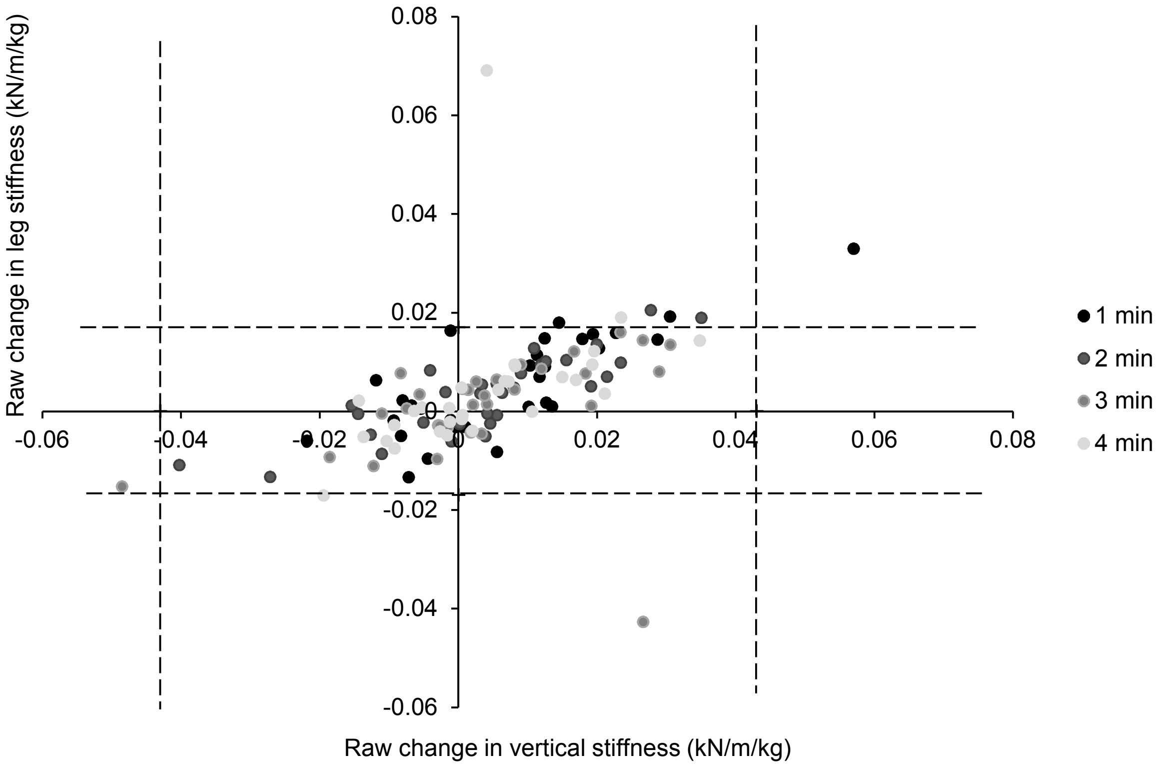

Figure 8.2: Raw change scores for vertical and leg stiffness for the first four minutes of a run following a 30 minute cycle

Dashed lines represent difference of 10% of the IR mean.

Figure 8.2 shows that leg and vertical stiffness tended to respond similarly in most athletes. If vertical stiffness decreased so did leg stiffness and if vertical stiffness increased so did leg stiffness (r = 0.80 at 1 min). Correlation was strongest for the first two minutes (r = 0.43 at 4 min). The majority of change scores are clustered around zero or no change in stiffness. However, a few individuals showed a notable increase or decrease in vertical and/or leg stiffness.

A plot of the raw change scores for knee and ankle stiffness does not show a clear correlation. Many of the athletes showed no change in knee and ankle stiffness following 30 minutes of cycle, with data points clustered around zero. The large amount of scatter indicates that some athletes had individual responses with combinations of both increases and decrease in knee stiffness with increased ankle stiffness.

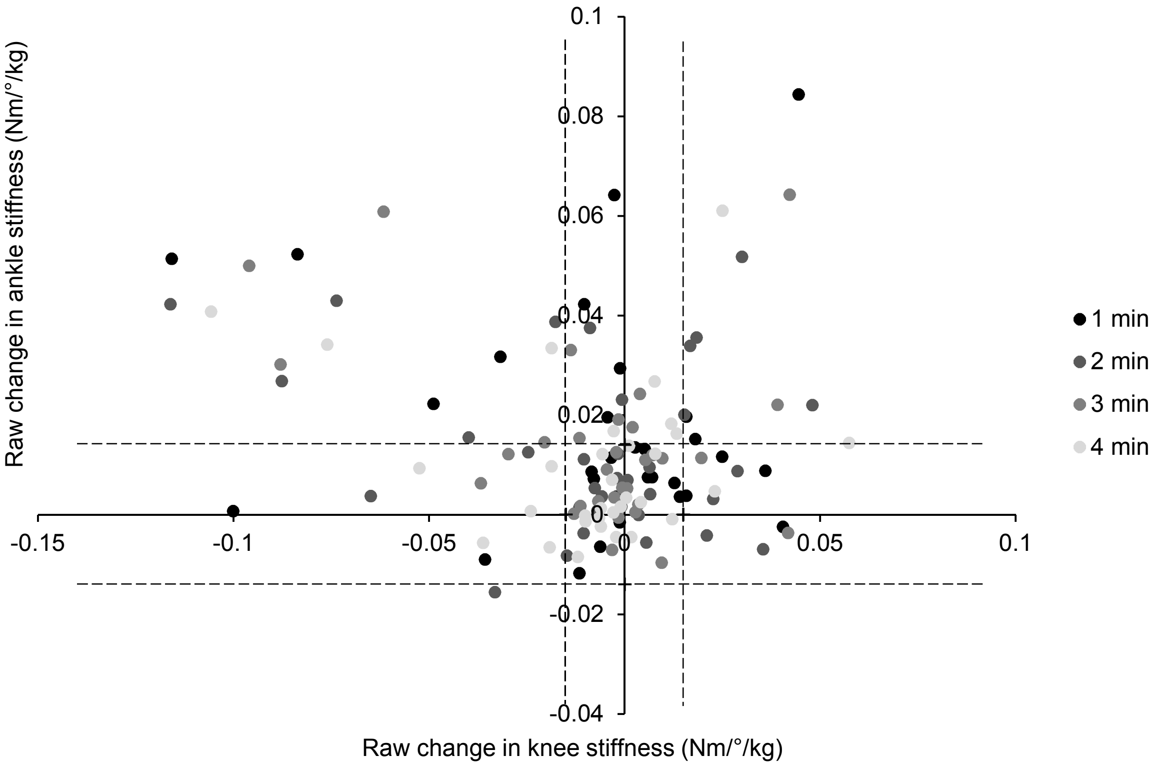

Figure 8.3: Raw change scores for knee and ankle stiffness for the first four minutes of running following a 30 minute cycle

Dashed lines represent difference of 10% of the IR mean.

Discussion

On average there were small to moderate changes in the mean vertical, leg and ankle stiffness for the first 1-2 minutes of running following cycling. The large confidence intervals indicate that there was a large amount of variation in the data which is confirmed with noticeable individual responses (Figures 8.2 and 8.3). For the majority of the triathletes tested, 30 minutes of self-paced cycling had little effect on any of the stiffness measures. This finding is fairly consistent with the study by Le Meur et al. (214) who found that 30 minutes of cycling at ~80% VO_{2max} followed by a run at lactate threshold resulted in significant but unclear increases in leg stiffness and vertical stiffness compared to an isolated run at lactate threshold (279). Average vertical stiffness was similar between the two studies for the IR condition however a smaller increase in vertical stiffness was observed for our study at one minute into the TR compared to that reported by Le Meur et al. (214) at 5% of a ~15±4 minute run. Absolute leg stiffness was lower in our results but increased by approximately the same amount as reported by Le Meur et al. (214). The difference in change in vertical stiffness could be the result of differences in running pace, which was faster in the lactate threshold run (3.82 min/km) used by Le Meur et al.

(214). It has been previously established that vertical stiffness is increased with running pace (180, 267, 292).

Changes in leg and vertical stiffness in some athletes could be the result of a change from optimal gait parameters following cycling. Changes in muscle recruitment (230), kinematics (315) or both (225) could be factors resulting in stiffness which is suboptimal for the running pace utilised. As with the current study, previous research has shown that only some athletes demonstrate altered movement patterns (225, 230, 315). Le Meur et al. (214) reported an increase in flight time and maximal vertical force (F_{max}) and a decrease in contact time and change in leg length at 5% of the run off the bike. By decreasing contact time and increasing flight time, stride rate and stride length can be maintained (214). Reductions in contact time are associated with increases in both vertical and leg stiffness (175, 178, 185, 186). Such changes to stride parameters would support the trend of the data reported here. Increasing F_{max} alone requires increased vertical and leg stiffness to resist compression of the 'leg spring'. A stiffer 'spring' facilitates a more rapid rebound allowing shorter contact time. An increase in flight time is a logical result of greater rebound, however if stride length and stride rate remain constant the increased flight time will cause increased vertical excursion during flight. This could account for the increased cost of running often associated with running after cycling (224, 226). The direction of force application to the ground is suboptimal resulting in a COM trajectory which expends energy in excess vertical motion. Greater muscular energy is also required in order to maintain the stiffer leg to allow for stable running under these conditions. The correlation between vertical and leg stiffness change scores was strongest in the first two minutes, suggesting that the gait changes leading to increased stiffness were common parameters to both measures, most likely increases in F_{max} and decreases in contact time (175, 177, 178, 185, 186).

While increased vertical excursion during flight may explain the general trend of the data, the scatter of the data (Figure 8.2) suggests a variety of responses. Different temporal and kinematic responses have been reported in the literature including increased stride rate with decreased stride length (92), increased stride rate with similar stride length (303), and both increases and decreases in COM displacement (226). The effect of fatigue on vertical and leg stiffness were variable (279). In a treadmill run to exhaustion at ~80% VO_{2peak} however, both vertical and leg stiffness showed small decreases in stiffness (177, 279). Fatigue following prolonged exercise could result in reduced muscle force production and cause reduced stiffness in some athletes. Alternatively there could be a delay in switching from the pattern of muscle activation required for cycling to an optimal running pattern. A lack of proper coordination of muscle activation could cause application of force at a suboptimal angle altering flight trajectory with accompanying kinematic changes. Interestingly, both vertical and leg stiffness tended to drop below the baseline level as the run progressed, supporting the notion that reduced stiffness responses are the result of fatigue.

An alteration in movement control is more apparent when looking at the response of the individual joints. While ankle stiffness tended to be increased, when a stiffness change was present, knee stiffness both increased and decreased following cycling. Decreasing contact time is associated with increasing ankle stiffness (183, 188). The increase in ankle stiffness in this study, is therefore in agreement with the findings of decreased contact time and increased flight time by Le Meur et al. (214). During hopping, increasing the intensity resulted in decreased contact time, increased flight time through increased knee and ankle stiffness (202). Similarly, increasing hopping height from 50% to 100% of maximum resulted in increased knee and ankle stiffness (188). Therefore, a decrease in contact time and increase in flight time appears to fit with the increased knee and ankle stiffness observed in some of the athletes. Those athletes responding with increased knee and ankle stiffness compared to the control run, appear to be working harder to maintain the same running speed. In a run to exhaustion with periods of manipulated step rate, both increasing and decreasing stride rate resulted in increased energy cost of running (206). Increasing stride rate from 8% below the preferred stride rate to 8% above resulted in increases in both vertical and leg stiffness (206). Therefore, adjustment of the stiffness parameters either above or below the athletes preferred or natural levels requires greater energy expenditure.

Studies utilising hopping and running tasks have shown that changing the task constraint, such as contact time (183, 188), frequency (187, 193) and intensity (202) resulted in reciprocal changes to knee and ankle stiffness. Some triathletes in this study showed similar coordination between the knee and ankle, with increases in stiffness at both joints. Individuals who increase ankle stiffness but decrease knee stiffness, increased ankle stiffness alone or altered knee stiffness alone appear to have uncoupled knee and ankle stiffness within the movement. Decreasing surface stiffness during hopping tasks has shown similar uncoupling between the knee and ankle with knee stiffness decreasing and ankle stiffness increasing (143). Low surface stiffness was clearly associated with an increase in risk of Achilles tendon injuries (167), therefore athletes who respond to running following cycling with increased ankle stiffness but decreased knee stiffness may be at greater risk of injury during this time.

Changing the relative contribution of the knee and ankle to the stiffness of the system could result in alteration of the loading to the Achilles tendon. The medial and lateral gastrocnemius and the soleus all contribute to the Achilles tendon. The mono-articular soleus muscle controls ankle plantarflexion. The bi-articular gastrocnemius muscles however contributes to ankle plantarflexion and knee flexion. Increasing knee flexion causes active insufficiency in the gastrocnemius reducing the force production capability. This has been shown to contribute to shearing within the tendon (74). Altering the relative contribution of the knee and ankle could further increase the shearing stress within the tendon which may be a mechanism for Achilles tendon overuse injuries. Changing the relative contribution of the triceps surae muscles has been shown to alter the force distribution within the tendon (154). Therefore, changing the balance between knee and ankle stiffness could result in greater tensile load to a portion of the tendon resulting in microscopic ruptures (61, 154). Should loading occur before sufficient healing has occurred a cycle of degeneration may be initiated leading to gradual weakening of the tendon and expansion of the region of scarring (43, 167). Maintaining balance of force applied to the Achilles tendon via the triceps surae muscles may be important for maintaining tendon health.

Further research is needed looking at the correlation between COM displacement, stride length, stride rate, stance length and joint angles and moments with lower limb stiffness for isolated run and running following cycling to see how the different parameters change with respect to each other. This may give more insight into what changes are occurring in those athletes that do show altered kinetics and/or kinematics when running following cycling. Future analysis should look at responders and non-responders as separate groups in order to avoid changes being masked by group effects. Prospective injury analysis would identify whether people who respond to running following cycling with altered movement patterns are more at risk of injury and if so which movement patterns lead to which injuries.

Conclusions

The gait mechanics of the majority of triathletes appear to remain unchanged following 30 minutes of self-paced cycling. A small number of athletes responded to running following cycling by adjusting knee and ankle stiffness in different ways. In those athletes that respond with an altered movement pattern following cycling, the general trend supports an increase in flight time and a decrease in contact time. This could explain why the cost of running increases following cycling if energy is being expended for unnecessary vertical movement. A few athletes responded with decreased knee stiffness but increased ankle stiffness. Stiffness alterations that occur in opposition at the knee and ankle may indicate an uncoupling of movement coordination and could be related to increased risk of tendon injury.

CHAPTER 9

LOWER LIMB STIFFNESS FOR THE PREDICTION OF ACHILLES TENDON INJURIES IN TRIATHLETES: A PROSPECTIVE STUDY

This chapter comprises the following paper:

Lorimer, A., Hume, P. Lower limb stiffness for the prediction of Achilles tendon injuries in triathletes: A prospective study**.** To be submitted to *British Journal of Sports Medicine*.

Overview

Background: Achilles tendon injuries are frequent and costly in athletes. Lower limb stiffness is a risk factor that could have the potential to predict Achilles tendon injury.

Aim: Assess the ability of lower limb stiffness measures to predict risk of Achilles injuries in triathletes.

Methods: Baseline screening of lower leg stiffness followed by prospective self-reported injury surveillance of one year for 75 competitive New Zealand triathletes. Lower leg (vertical, leg and joint) stiffness was calculated from three-dimensional video and force data during treadmill running at 5.5, 5.0, 4.5 and 4.0 min/km (3.0, 3.3, 3.7 and 4.2 m/s). Effect sizes were calculated for three injury groups (First Achilles injury [FirstAchilles], prior Achilles + Achilles injury during surveillance year [PriorAchilles], prior Achilles injury without injury during the surveillance year [PriorUninjured]) compared to uninjured athletes (no lower body injury during the surveillance year + no prior Achilles injuries [Uninjured]).

Results: Of the 75 triathletes, 21% had sustained an Achilles injury either prior or during the study (sample size was FirstAchilles n=3; PriorAchilles = 4; PriorUninjured = 9; Uninjured = 23). Leg stiffness was increased in those who developed an Achilles injury (ES= 0.29; 95% CI -0.34–1.18 PriorAchilles: 0.76; -0.17–2.07 FirstAchilles) compared to uninjured athletes. Knee stiffness was higher with respect to ankle stiffness (knee to ankle stiffness ratio) (k_{knee}/k_{ankle} ES= 0.60; 95% CI -0.10–1.58 PriorAchilles: 0.93; -0.02–2.26 FirstAchilles) in triathletes who developed Achilles injuries during the surveillance period.

Discussion: High leg stiffness and knee to ankle stiffness ratio predicted Achilles tendon injury in competitive triathletes. Leg stiffness is a measurement which could provide initial screening to identify athletes who require specific joint stiffness analysis. An imbalance between the knee and ankle stiffness appears to result in overloading of the Achilles tendon. The exact nature of the imbalance is unclear but treatment should likely focus on balancing agonist/antagonist strength at the knee and ankle and limiting factors which could increase knee stiffness further such as running on soft surfaces

(sand), at fast paces or in overly cushioned shoes. Further research is required to consolidate these findings due to the small injury numbers.

Conclusions: Increased knee stiffness compared to ankle stiffness appears to provide information on a triathlete's risk of developing a new Achilles or reoccurrence of a previous Achilles injury.

Introduction

Achilles injuries frequently result in reoccurrence of pain and dysfunction and are classified as one of the most severe triathlon injuries in terms of number of training days lost (16, 167). Eccentric training is reported to be effective in reducing pain in many cases and is the first treatment option, however many athletes resort to surgery due to multiple reoccurrences of pain and dysfunction (34, 316, 317). As a result, Achilles injuries have substantial financial and emotional costs at all performance levels.

High braking forces, high arches and soft surfaces have been identified as clear risk factors for Achilles overuse injuries (167). However, overuse injuries are likely to be multifactorial in nature. Any multi-segment movement has a number of routes by which the movement can be achieved, resulting in movement variation within a population (160). A combination of factors could provide enough stress to the tissue to cause progressive tissue deterioration. The end result is the same however via a number of alternative routes.

Many biomechanical variables have been identified as possible risk factors for the development of Achilles tendon injuries in running athletes (167). Many of these individual risk factors (e.g. running pace, contact time, training status, intensity, muscle activity) can alter stiffness of the lower limbs during cyclical motion such as hopping or running (279). Therefore, it may be possible to use lower limb stiffness measures to represent the combined effects of these individual risk factors on developing Achilles tendon injuries. Small differences in individual risk factors are unlikely to show statistically valuable results, however investigating combinations may provide the answers that have previously been lost in the natural variation of movement and measurement.

Stiffness of the lower limbs can be measured during running and hopping in clinical assessments. Running is a bouncing gait and has been modelled as a point mass supported by a compressible spring (159, 170). Compression of the 'leg-spring' in response to landing force is achieved through rotation of the joints, modelled as torsional springs (143). Stiffness of the spring is a measure of resistance to compression or rotation. Higher stiffness indicates greater resistance to compression and is observed as reduced joint rotation, 'leg spring' compression and centre of mass vertical displacement. Greater muscle activity to resist rotation, increasing joint moments or reduced force for similar muscle activity, result in increased joint stiffness. Tendons and ligaments also play a role in modifying rotation and moments but are less modifiable from step to step. Lower limb stiffness is a risk factor for Achilles tendon injuries (167, 279).

Aim

The aim of this study was to assess the ability of a variety of lower limb stiffness measures to predict risk of Achilles injuries in triathletes.

Methods

Athlete characteristics

Seventy-five triathletes (45 male; 34.1±9.9 years, 76.1 ±7.1 kg, 1.80 ±0.06 m and 30 female; 31.0±8.3 years, 62.1 ±5.6, 1.69 ±0.06 m) volunteered for the research. All triathletes were currently competitive as professional or top level age group Olympic distance and long distance athletes. Personal best times in the previous season of 2h 20 min/ 2h 40 min (male/female) for Olympic distance and 10 h/ 11h 30 min (male/female) for Iron distance and the ability to run for over 2 min at 4.0 min/km was required. Triathletes were free from any lower limb injuries at the beginning of the study period and had been back to full training for at least six weeks following any previous injury. All athletes provided fully informed written consent prior to participation. Ethical approval was obtained for all testing procedures from the university ethics committee.

Procedures

A treadmill graded run task was performed by the triathletes. Running pace was not randomized in order to reduce injury risk and to allow inter-subject comparisons at the increasing running paces.

Following warm-up and familiarization of 5 min at 6.0 min/km (2.8 m/s), triathletes ran for two minutes each at 5.5, 5.0, 4.5 and 4.0 min/km (3.0, 3.3, 3.7 and 4.2 m/s). A jogging or walking cool-down was given. All acceleration and deceleration between running pace blocks were set to 0.1 m/s^2. Data were collected for the final 20 s of each two minute block in order to ensure gait had stabilized following pace change. Athletes were unaware of when recording was taking place.

All triathletes wore spandex shorts or trisuits and their own regular training shoes. Height, weight and bilateral trochanterian height were recorded according to International Society for the Advancement of Kinanthropometry (ISAK) protocols (259). Retroflective markers (10 mm) were attached to the lower body according to a modified three dimensional (3D) model (Figure 9.1) (280). Following a static standing calibration, femoral condyl and malleoli markers were removed. For dynamic calibration of the hip joint, participants moved first the right then the left leg through a combination of flexion, abduction, adduction and extension (260, 263). Knee joint center dynamic calibration involved three shallow squat movements (260).

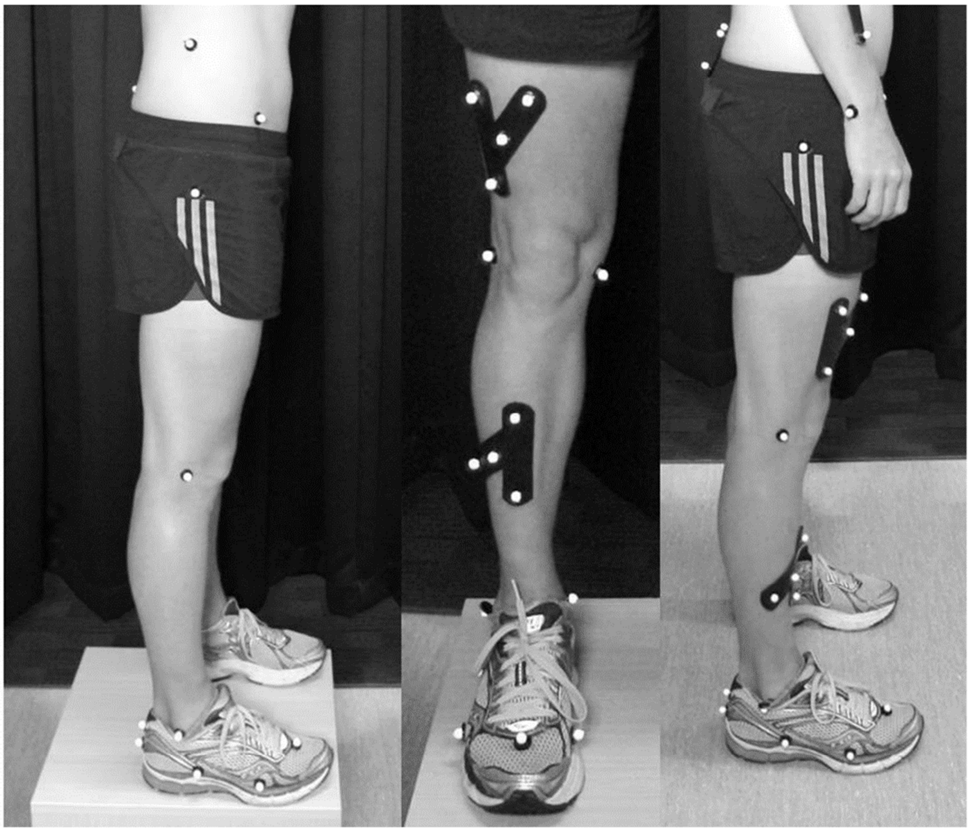

Figure 9.1: Lower body marker locations without and with tracking clusters

Data collection and analysis

A 9-camera VICON motion analysis system (Oxford Metrics Ltd., Oxford, UK) combined with a Bertec instrumented treadmill (BERTEC Corp, Worthington, OH, USA) were used for kinematic (200 Hz) and ground reaction force (1000 Hz) collection, respectively. Functional joint positions were determined using a custom built, MATLAB constrained optimization program (*Optimization Toolbox,* Mathworks Inc.; Natick, MA) detailed by Besier et al. (260). Joint angles and moments were calculated via inverse kinematics using Visual3D software (*Visual3D™,* C-motion, Inc.; Rockville, MD). Anatomical co-ordinate systems were defined according to specifications reported by Besier et al. (260) and Lorimer et al. (280).

Variables were averaged over ten steps per leg for each individual. Horizontal velocity was taken as treadmill velocity and was assumed to be constant. Vertical, leg and joint stiffness were assessed for association with injury. Stiffness values were normalized to body weight before statistical analysis.

Stiffness calculations

Stiffness values were calculated using a custom written Labview program (*Labview,* National Instruments Corp.; Austin, Tx). Stiffness was calculated for the first half of stance from initial heel contact to maximal vertical ground reaction force for all stiffness measures (242). Stiffness calculations were carried out using the equations in Table 9.1.

Table 9.1: Biomechanical stiffness model calculations, variables and equipment

Stiffness calculation	Terms list	Key variables
Vertical stiffness		
$k_{vert/time} = \frac{F_{max}}{\Delta y}$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta y = -\frac{F_{max}}{m}\frac{t_c^2}{\pi^2}+g\frac{t_c^2}{8}$	F_{max} = peak vertical force, Δy = centre of mass displacement, m = subject mass, t_c = contact time, t_f = flight time, g = acceleration due to gravity.	Contact time (243)
Leg stiffness		
$k_{leg/time} = \frac{F_{max}}{\Delta L}$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta y = -\frac{F_{max}}{m}\frac{t_c^2}{\pi^2}+g\frac{t_c^2}{8}$ $\Delta L = L_0 - \sqrt{L_0^2-\left(\frac{vt_c}{2}\right)^2} + \Delta y$	F_{max} = peak vertical force, ΔL = change in leg length, Δy = centre of mass displacement, L_0 = trochanterian height, m = subject mass, t_c = contact time, t_f = flight time, g = acceleration due to gravity, *v* = horizontal velocity	Contact time Horizontal velocity Standing leg length (243)
Joint stiffness		
$k_{joint} = \frac{\Delta M}{\Delta \theta}$	ΔM = change in joint moment, Δθ = change in joint angle	Three dimensional force Lower body video for inverse dynamics calculation (240, 244)

Joint stiffness combinations, $k_{sumjoints}$, $k_{hip+knee}$ and $k_{knee+ankle}$ were calculated using equations 1-3.

$$k_{sumjoints} = k_{hip} + k_{knee} + k_{ankle} \quad (1)$$

$$k_{hip+knee} = k_{hip} + k_{knee} \quad (2)$$

$$k_{knee+ankle} = k_{knee} + k_{ankle} \quad (3)$$

Injury data

All prior injuries suffered by the athletes were recorded at the initial baseline laboratory session. Athletes' injuries were then recorded prospectively for one year. Every month athletes were sent a link to an online questionnaire (SurveyGizmo; Boulder, CO, USA) asking if they had suffered a new injury in the past month and if so details were collected on location, side, diagnosis, activity attributed to injury, treatment and impact on training and racing.

Athletes were grouped by injury status as:

prior Achilles tendon injury but no injury in the 1-year surveillance period (PriorUninjured);

prior Achilles tendon injury and injury in the 1-year surveillance period (PriorAchilles);

no prior Achilles tendon injury but an Achilles injury in the 1-year surveillance period (FirstAchilles);

no prior Achilles tendon injury and no lower limb injury in the 1-year surveillance period (Uninjured).

AllAchilles was the term used for the FirstAchilles and the PriorAchilles groups combined.

Statistical analyses

Descriptive statistics for all variables were calculated as least squares means with 95% confidence intervals to account for unbalanced data. An intention-to-treat analysis was carried out on the data. Missing data prevented analysis of the 4.0 min/km pace and leg stiffness in the PriorAchilles group.

Differences in stiffness between the four injury status groups of athlete were assessed using Proc Mixed in SAS. The least squares mean, differences of least squares mean (%), coefficient of variation (CV%) and 95% confidence intervals were extracted. Effect sizes were calculated from the differences of least squares mean and combined group standard deviation. Effect size thresholds for trivial, small, moderate and large effects were 0.2, 0.6, 1.2 and 2.0 (121). Post hoc analysis was performed for the ratio between knee to ankle stiffness (k_{knee}/k_{ankle}) using the same methodology.

Effect sizes for the different stiffness measures averaged over running paces (diamond) and for the individual paces (circles) for the comparisons PriorUninjured v Uninjured, PriorAchilles v Uninjured and FirstAchilles v Uninjured are presented in Figure 9.2. A positive effect size indicates the stiffness in the group on the left of the comparison (i.e. PriorUninjured, PriorAchilles or FirstAchilles) increased compared to the Uninjured group. A negative effect size indicates a decrease in stiffness compared to the Uninjured group.

Results

Analysis of the participant characteristics for the triathletes and their injury status confirmed there was no significant difference in age between any of the groups.

Questionnaire response rate was high at 71%. Three athletes were lost to all injury surveillance, 11 within three months, a further nine after six months and a further five after nine months, leaving 62% of athletes reporting injuries over the entire 1-year surveillance period.

Seven triathletes (four in PriorAchilles, three in FirstAchilles) reported Achilles tendon injury over the 1-year. Nine athletes reported prior injuries at baseline but remained uninjured during the 1-year surveillance (PriorUninjured). Twenty three triathletes had no Achilles injuries either prior to the study and no lower limb or lower back injuries during the 1-year surveillance (Uninjured).

Table 9.2: Least squares mean stiffness (95% confidence interval) measures for the different injury groups at the four running paces

		Uninjured		PriorUninjured		PriorAchilles		FirstAchilles	
	Pace (min/km)	LSM	95% CI	LSM	95% CI	LSM	95% CI	LSM	95% CI
$k_{vertical/time}$ (kN/m/kg)	5.5	0.37	(0.36:0.38)	0.35	(0.34:0.37)	0.37	(0.36:0.38)	0.41	(0.37:0.45)
	5.0	0.39	(0.37:0.40)	0.38	(0.36:0.40)	0.39	(0.37:0.40)	0.42	(0.37:0.48)
	4.5	0.42	(0.41:0.44)	0.40	(0.38:0.42)	0.42	(0.41:0.44)	0.45	(0.41:0.50)
	4.0	0.46	(0.45:0.48)	0.46	(0.44:0.49)			0.51	(0.46:0.56)
$k_{leg/time}$ (kN/m/kg)	5.5	0.17	(0.16:0.17)	0.16	(0.15:0.17)	0.17	(0.16:0.19)	0.19	(0.17:0.21)
	5.0	0.16	(0.16:0.17)	0.16	(0.15:0.18)	0.17	(0.15:0.19)	0.19	(0.16:0.22)
	4.5	0.16	(0.16:0.17)	0.15	(0.14:0.16)	0.16	(0.15:0.17)	0.17	(0.16:0.19)
	4.0	0.16	(0.15:0.17)	0.16	(0.15:0.17)			0.18	(0.16:0.20)
$k_{sumjoints}$ (Nm/°/kg)	5.5	0.46	(0.44:0.49)	0.38	(0.35:0.43)	0.39	(0.33:0.47)	0.47	(0.40:0.56)
	5.0	0.48	(0.45:0.51)	0.41	(0.38:0.45)	0.43	(0.35:0.53)	0.52	(0.41:0.65)
	4.5	0.51	(0.49:0.54)	0.43	(0.39:0.47)	0.57	(0.53:0.61)	0.47	(0.39:0.57)
	4.0	0.57	(0.53:0.61)	0.45	(0.41:0.49)			0.50	(0.42:0.59)
$k_{hip+knee}$ (Nm/°/kg)	5.5	0.33	(0.31:0.36)	0.27	(0.23:0.30)	0.29	(0.23:0.36)	0.35	(0.28:0.44)
	5.0	0.34	(0.32:0.37)	0.29	(0.26:0.32)	0.32	(0.25:0.41)	0.39	(0.29:0.52)
	4.5	0.36	(0.34:0.39)	0.29	(0.26:0.33)	0.40	(0.36:0.43)	0.34	(0.27:0.43)
	4.0	0.40	(0.36:0.43)	0.30	(0.27:0.34)			0.35	(0.29:0.44)
$k_{knee+ankle}$ (Nm/°/kg)	5.5	0.25	(0.24:0.27)	0.22	(0.20:0.25)	0.23	(0.19:0.28)	0.28	(0.24:0.33)
	5.0	0.26	(0.25:0.28)	0.24	(0.22:0.26)	0.26	(0.21:0.33)	0.32	(0.25:0.41)
	4.5	0.29	(0.27:0.31)	0.25	(0.23:0.28)	0.33	(0.30:0.35)	0.30	(0.24:0.36)
	4.0	0.33	(0.30:0.35)	0.27	(0.25:0.30)			0.33	(0.28:0.40)
k_{hip} (Nm/°/kg)	5.5	0.20	(0.19:0.22)	0.16	(0.13:0.18)	0.16	(0.12:0.22)	0.19	(0.15:0.25)
	5.0	0.20	(0.18:0.23)	0.17	(0.14:0.19)	0.17	(0.12:0.23)	0.20	(0.13:0.29)
	4.5	0.21	(0.19:0.23)	0.17	(0.14:0.20)	0.23	(0.20:0.26)	0.17	(0.13:0.24)
	4.0	0.23	(0.21:0.26)	0.17	(0.14:0.20)			0.17	(0.13:0.23)
k_{knee} (Nm/°/kg)	5.5	0.12	(0.11:0.13)	0.10	(0.09:0.12)	0.13	(0.09:0.18)	0.16	(0.12:0.21)
	5.0	0.13	(0.11:0.14)	0.11	(0.10:0.13)	0.15	(0.10:0.22)	0.19	(0.13:0.29)
	4.5	0.14	(0.12:0.15)	0.12	(0.10:0.14)	0.15	(0.14:0.17)	0.16	(0.12:0.23)
	4.0	0.15	(0.14:0.17)	0.13	(0.11:0.15)			0.18	(0.13:0.25)
k_{ankle} (Nm/°/kg)	5.5	0.13	(0.12:0.13)	0.12	(0.11:0.13)	0.10	(0.12:0.14)	0.12	(0.10:0.14)
	5.0	0.13	(0.13:0.14)	0.12	(0.11:0.13)	0.12	(0.13:0.14)	0.13	(0.10:0.16)
	4.5	0.15	(0.14:0.16)	0.13	(0.12:0.14)	0.17	(0.14:0.16)	0.13	(0.11:0.16)
	4.0	0.17	(0.16:0.18)	0.14	(0.13:0.15)			0.15	(0.13:0.17)
k_{knee}/k_{ankle}	5.5	0.94	(0.86:1.04)	0.90	(0.76:1.08)	1.21	(0.88:1.68)	1.32	(0.98:1.78)
	5.0	0.93	(0.83:1.04)	0.93	(0.77:1.11)	1.23	(0.88:1.73)	1.52	(0.98:2.37)
	4.5	0.92	(0.83:1.02)	0.88	(0.73:1.06)	1.37	(0.91:2.06)	1.23	(0.86:1.78)
	4.0	0.91	(0.81:1.03)	0.90	(0.74:1.08)			1.26	(0.92:1.73)

Vertical (ES= 0.75; 95% CI -0.18–2.04) and leg (0.76; -0.17–2.07) stiffness showed moderate increases for FirstAchilles compared to Uninjured. Only leg stiffness was increased compared to Uninjured for the PriorAchilles group (0.29; -0.34–1.18). The PriorUninjured group had trivial to small decreases in vertical (-0.25; -0.67–0.35) and leg (-0.23; -0.65–0.39) stiffness compared to the Uninjured group (see Table 9.2).

All injured groups had reduced ankle stiffness compared to the Uninjured group, with PriorAchilles (-0.92; -1.33–-0.26) having the greatest decrease in ankle stiffness. PriorUninjured had a small increase in knee stiffness (0.41; -0.17–0.79), while PriorAchilles had no difference (0.08; -0.53–0.96) and FirstAchilles had small to moderate increases in knee stiffness (0.73; -0.19–2.02).

Combined knee and ankle stiffness (-0.65; -1.00–-0.11) had a small to moderate decrease for PriorUninjured, a small decrease (-0.42; -0.94–0.37) for PriorAchilles and a small increase (0.38; -0.48–1.60) for FirstAchilles compared to Uninjured. The pattern of effect size distribution was most notable between the different injury groups (see Figure 9.2). The PriorUninjured v Uninjured analysis showed effect sizes clustered to the right (decreased stiffness). The two injury groups (PriorAchilles and FirstAchilles) however, had ankle stiffness to the right and knee, leg and vertical stiffness to the left. PriorAchilles had all data shifted right compared to FirstAchilles.

Analysis of the ratio of knee to ankle stiffness (k_{knee}/k_{ankle}) showed that while there was no difference between PriorUninjured (-0.07; -0.52–0.56) and Uninjured, both PriorAchilles (0.60; -0.10–1.58) and FirstAchilles (0.94; -0.02–2.27) had moderately increased ratios compared to Uninjured. Large confidence intervals meant that the majority of results were unclear.

Using the between leg analysis for Uninjured and AllAchilles, differences in between-subject variability were assessed (Figure 9.3). While the confidence intervals were large and therefore overlapped (not shown) there appeared to be some difference in the between-subject variability. Both leg and knee stiffness had reduced variability in AllAchilles compared to Uninjured. The pattern of variability for knee stiffness was inverted for AllAchilles and ankle stiffness variability dropped rapidly as pace increased.

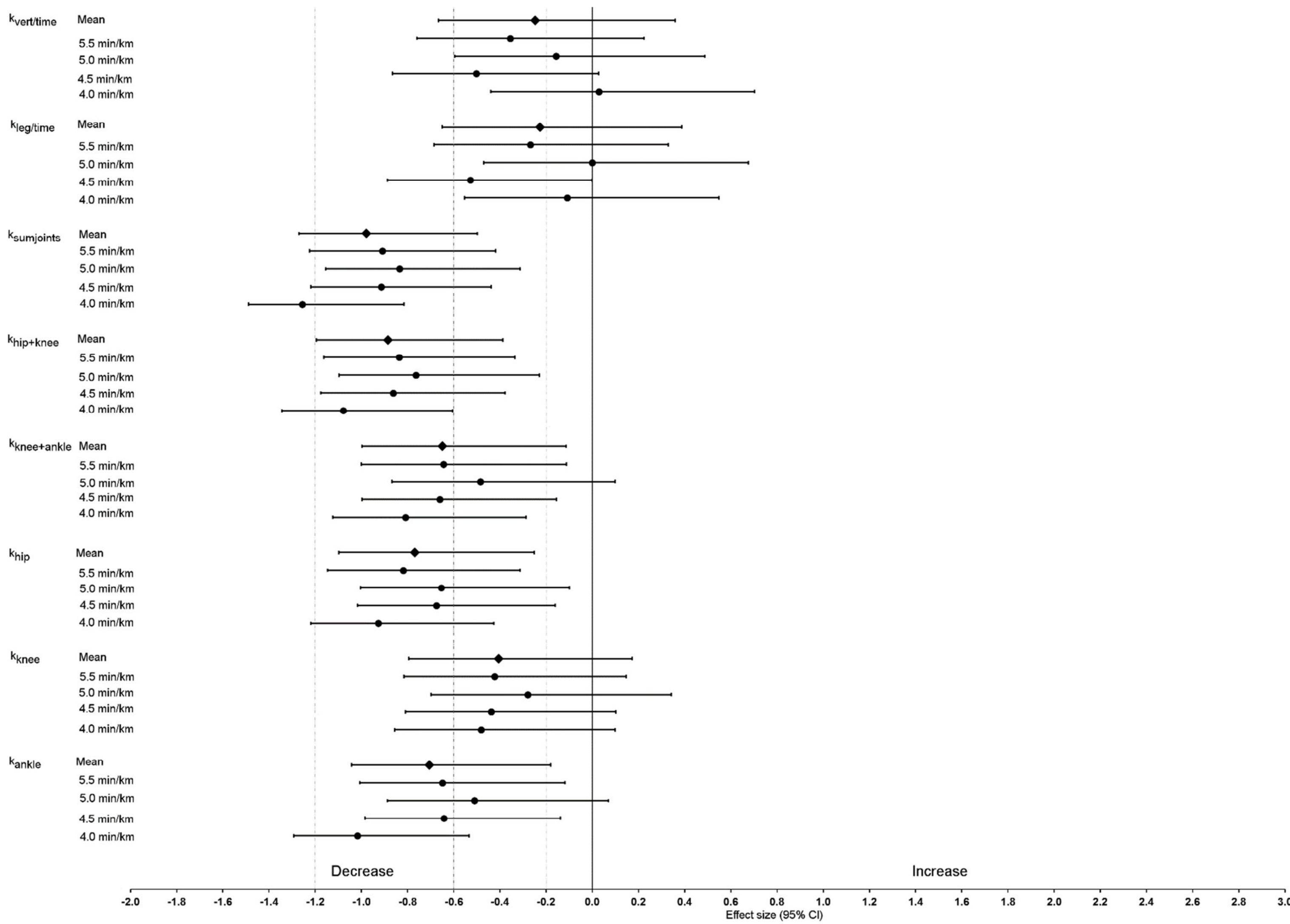

Figure 9.2: a). Comparison of stiffness measures between PriorUninjured and Uninjured groups

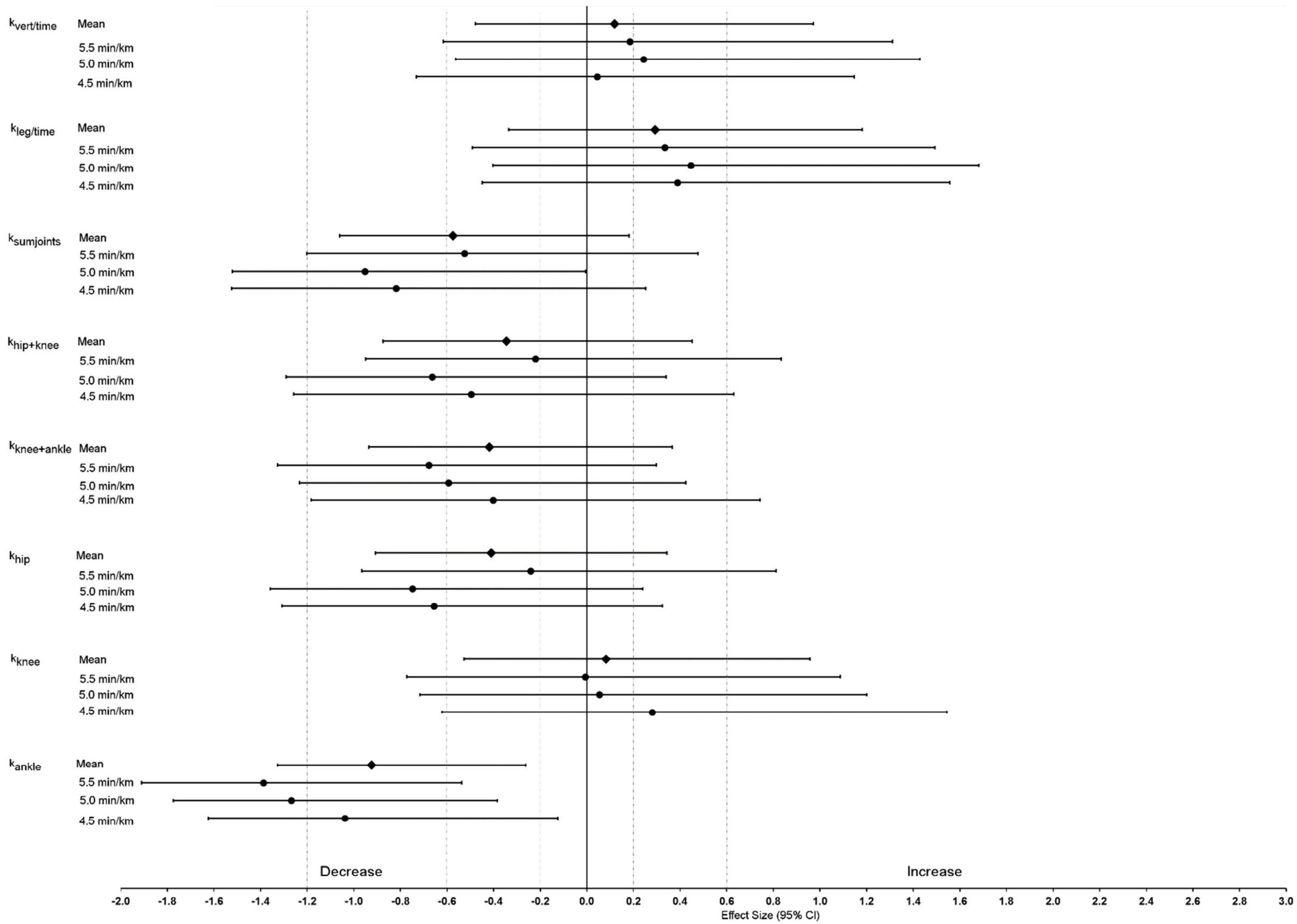

Figure 9.2 cont.: b). Comparison of stiffness measures between PriorAchilles and Uninjured groups

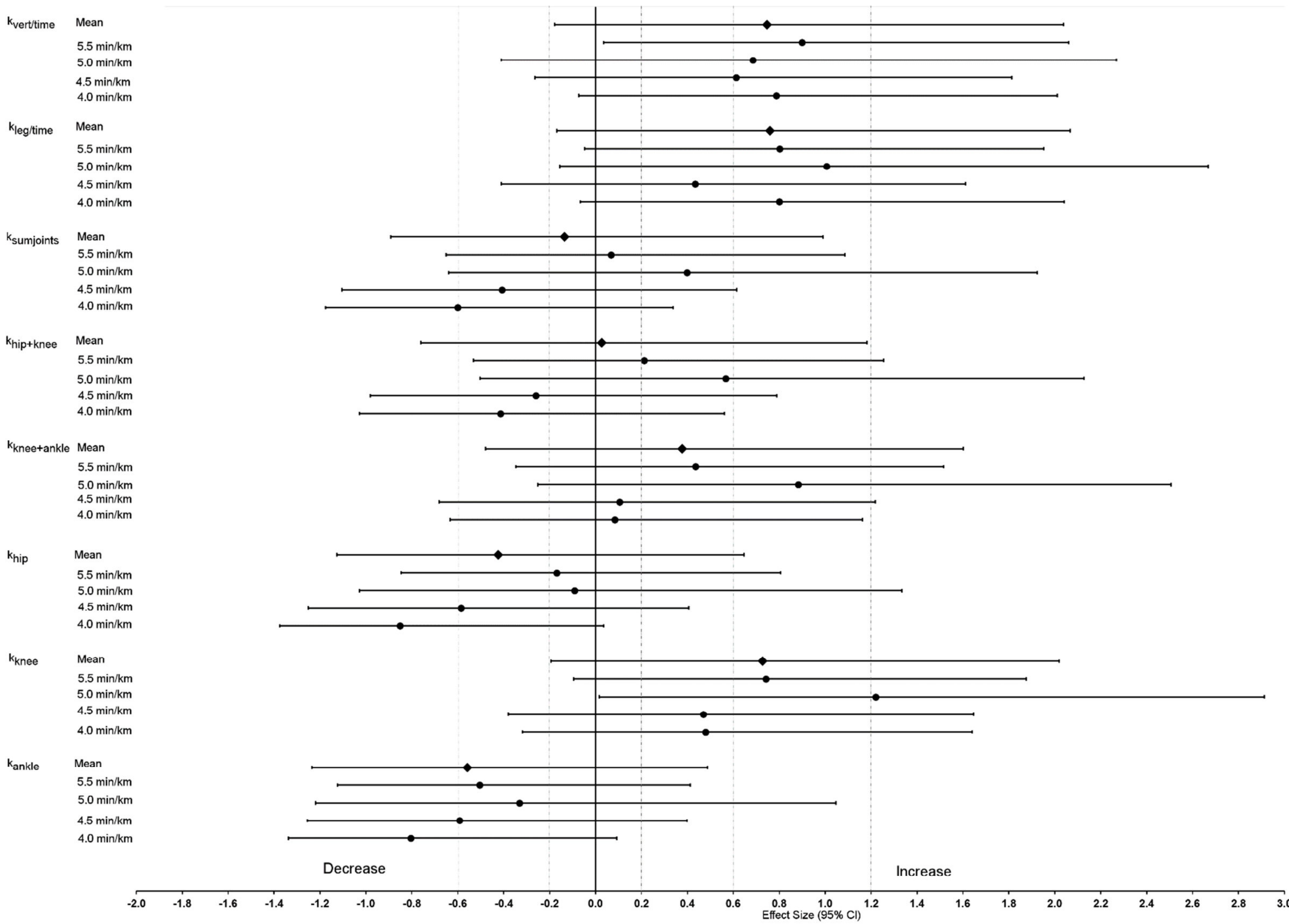

Figure 9.2 cont.: c). Comparison of stiffness measures between FirstAchilles and Uninjured groups

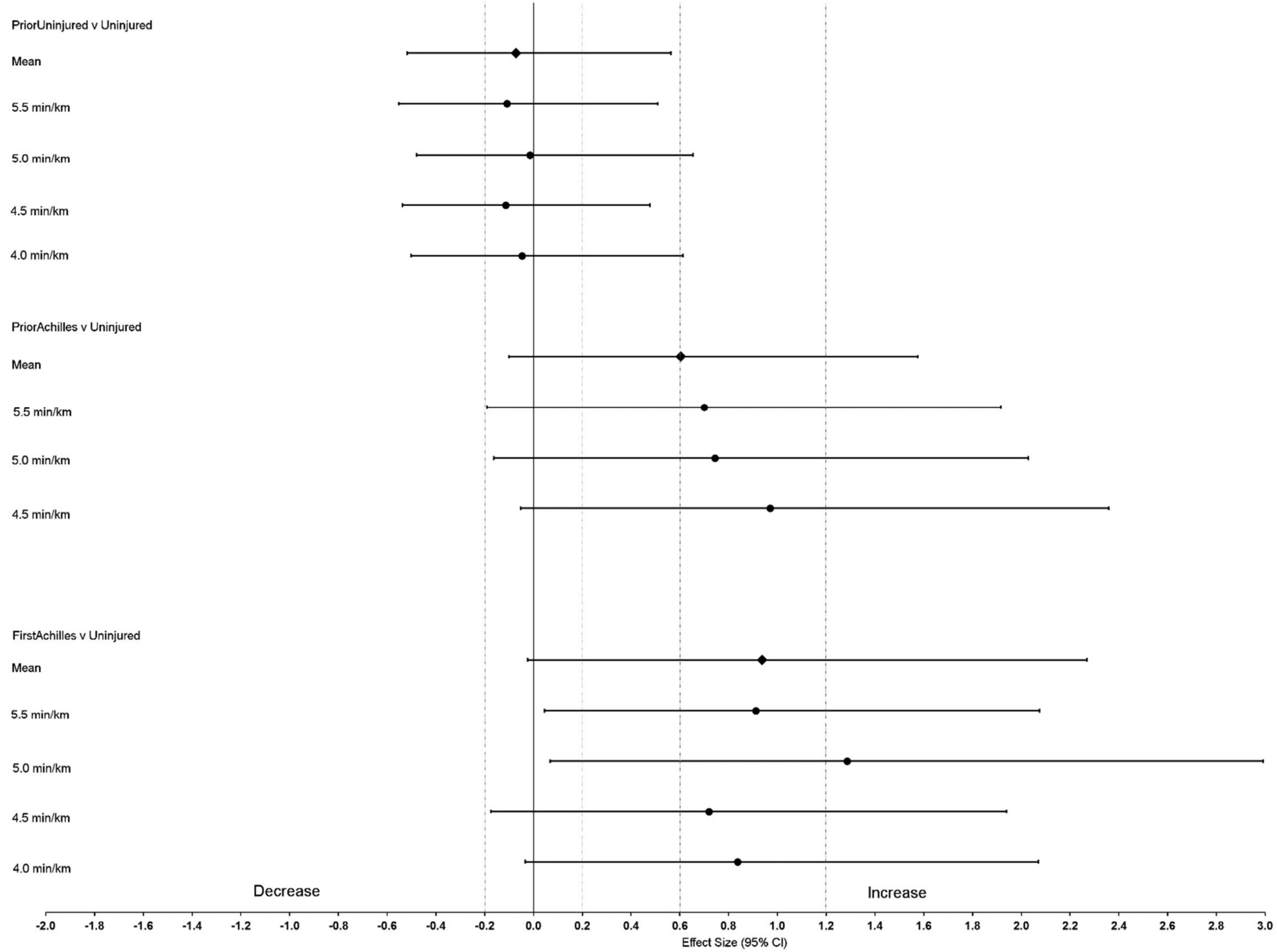

Figure 9.2: d). Knee/ankle stiffness ratio, comparison of each group with the Uninjured group

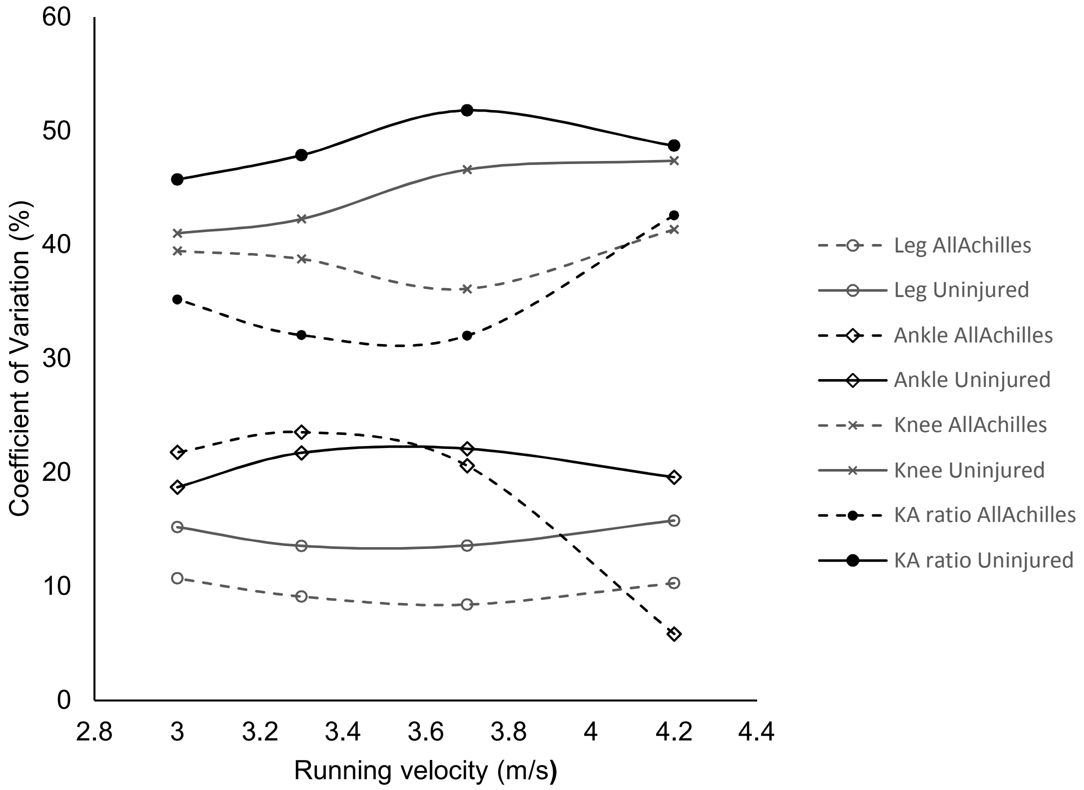

Figure 9.3: Between subject variability for various stiffness measures

Discussion

The results of this initial prospective injury study showed that reduced ankle stiffness and possibly increased knee and leg stiffness could be useful measures in predicting Achilles injury risk in triathletes. A new measure, knee/ankle stiffness ratio seemed to be the best indicator of injury risk.

In the PriorUninjured v Uninjured comparison, the effect sizes for k_{knee}, k_{ankle} and $k_{knee+ankle}$ were more or less aligned. However, in the two groups that developed an Achilles injury during the surveillance year (PriorAchilles and FirstAchilles) k_{knee} and k_{ankle} were separated to opposite sides of zero with the combined knee and ankle stiffness sitting somewhere in between.

The knee and ankle both play a role in the risk of Achilles tendon injury. In the majority of situations, changing the demands of the task resulted in similar changes to the knee and ankle stiffness (279, 292). Reducing surface stiffness, which has been identified as a risk factor for Achilles tendon injuries (167) however, resulted in decreased knee stiffness and increased ankle stiffness during hopping (143). While most athletes did not show altered stiffness measures when transitioning from cycling to running, some athletes responded with decreased knee stiffness and increased ankle stiffness (318). Therefore, it appears that the knee and ankle work together in most situations to modulate the stiffness of the system in order to achieve stable running (280). Situations where the balance between the knee and ankle is upset may be responsible for increasing the risk of injury to the Achilles tendon.

When investigating Achilles tendon function, both the knee and ankle play an important role due to the biarticular nature of the gastrocnemius. Experimentation has shown that shearing within the tendon differs in magnitude and direction depending on the orientation of the knee (74). A straighter knee reduces the degree of active insufficiency in the biarticular gastrocnemius allowing potentially more force to be generated from the gastrocnemius. As both the gastrocnemius and the soleus attach to the Achilles tendon, altering the force ratio between the soleus and gastrocnemius muscles would change the internal tendon collagen fascicle pull (154). The potential injurious results of this change include increased shearing stress within the tendon and increased tensile loading to individual collagen fascicles. Shearing stress can cause fascicle microdamage if occurring outside of the physiological angle of pull (71, 319). Increased tensile loading to collagen fascicles could lead to microscopic ruptures within the tendon (64). Both events while insignificant alone can trigger a cycle of progressively weakening tendon (64, 167) if the injurious loading is continued.

Increased knee stiffness was observed in the triathletes who sustained their first injury compared to uninjured triathletes. This however, was not the case for those who had had a prior Achilles injury which reoccurred. Both ankle and knee stiffness effect sizes moved towards the right, with ankle stiffness decreasing further with respect to the uninjured population, and knee stiffness decreasing by approximately the same amount. Therefore, the relative stiffness rather than the absolute stiffness measure may be the important risk factor for injury.

The difference in knee, ankle and combined knee and ankle stiffness profiles between the uninjured groups and the injured groups led us to calculate a new variable, the knee/ankle stiffness ratio. Individuals who went on to develop an Achilles injury during the surveillance year, showed increased knee stiffness compared to ankle stiffness, knee/ankle stiffness ratio greater than one. Those who remained uninjured had relatively similar knee and ankle stiffness or lower knee stiffness, with an average knee/ankle stiffness ratio of ~0.9.

The measurement of knee and ankle stiffness is more difficult than leg stiffness. Joint stiffness requires force and motion data in order to model joint moments, while leg stiffness can be estimated in its simplest form from contact time and flight time. Therefore, higher leg stiffness may provide a useful first step screening tool allowing the identification of individuals who may be at risk and require further analysis.

All groups who had had Achilles injuries at some time, had lower ankle stiffness compared to the uninjured triathletes. Different mechanisms could explain the decrease in ankles stiffness following Achilles injury. Achilles pain and dysfunction is believed to be the result of microtrauma in the tendon that progresses with continued loading (43). Changes in gait that allow the individual to reduce the pain experienced could be the cause of the observed decreased ankle stiffness. Decreased triceps surae muscle activity during stance could reduce the load on the Achilles tendon, allowing the individual to run with less pain but also resulting in reduced torque generated at the ankle joint.

The Alfredson eccentric ankle protocol (152) has become the most common treatment for Achilles tendon injuries. Debate remains as to how this exercise regime effects healing in the tendon and whether it is a stretching or a strengthening protocol (83). It is likely that individuals who have had prior Achilles tendon injuries have used eccentric exercises and incorporate them into their exercise schedule whenever pain re-emerges. The slow nature of the exercise would lead to stretching of the calf muscle and overtime could result in elongation of the triceps surae leading to the lower stiffness observed. Longer calf muscles would require greater contraction in order to enable efficient energy storage within the Achilles. Alternatively, excessive stretching could result in stretching of the Achilles which would then require greater muscular work or greater dorsiflexion in order to develop effective stretch shorten cycle action. Both actions could result in greater shearing loads within the tendon and/or tensile loading resulting in further damage and spiralling injury cycle.

It appears that those individuals who go on to develop chronic Achilles problems maintain a similar imbalance between knee and ankle stiffness, despite ankle stiffness being decreased even further. Therefore, it is important to correct this imbalance to prevent further repetitions of injury. Whether the imbalance in stiffness is the result of specific gait patterns (i.e. foot strike, joint coordination, stance time) or a muscle strength imbalance remains unclear. In triathletes a strength imbalance between the plantarflexor muscles and dorsiflexor muscles, or between the medial and lateral gastrocnemius can develop as a result of cycling technique or cycle set-up. Cycling is a primarily concentric activity (320, 321). Triathletes cycling with a toe down foot orientation, whether a natural cycle pattern or the result of a slightly too high saddle position increase the concentric load through the triceps surae and reduce the work of the tibailis anterior (322, 323). A high saddle position may also cause an inability to engage the gluteals and hamstrings causing the athlete to rely even more on their calf muscles to produce power (324). The effect of strength, cycling position and pedalling technique on the k_{knee}/k_{ankle} ratio should be investigated further.

Stiffness is a measure of how the different bones, joints, muscles, tendons and ligaments work together to produce the running movement pattern. The Achilles group may have a gait movement pattern that in some way caused overload or stress outside the normal physiological range leading to damage and degeneration to the tendon. Therefore, it is likely that injured triathletes have similar movement patterns and there will be less variability within these triathletes compared to the uninjured triathletes.

As predicted the athletes who developed an Achilles injury showed reduced between subject variability compared to the uninjured athletes for knee and leg stiffness and knee/ankle stiffness ratio. Knee stiffness and knee/ankle stiffness ratio showed inversion of the variability profile presented in uninjured athletes with variability tending to decrease with increasing pace (except for 4.0 min/km pace). The rather distinct increase in knee stiffness variability from 5.0 to 4.5 min/km pace may reflect the increased role of the knee in stabilising running gait (325), or may correspond with the increases in knee stiffness required to increase running pace, reported in two-segment modelling studies (171, 266). Athletes who developed an Achilles tendon injury did not modify knee stiffness to the same extent as uninjured athletes. The rapid drop in ankle stiffness variability may be a reflection of a decreased capacity of the ankle to modify stiffness with increasing pace, perhaps as a result of mechanical changes to the tendon or strength deficits. A better understanding of how the joint stiffness variability profiles relate to movement control may help to highlight why stiffness profiles are different in these athletes and how they can be modified to prevent injury.

Limitations

The number of injured athletes was small in the sample studied. While the knee and ankle are the most relevant joints to assess when investigating Achilles tendon injuries, the increased variability in the measurement when looking at the individual joints means that small differences between groups can be lost. However, combining the joints as the knee+ankle improved the reliability of the measurement, therefore the knee/ankle stiffness ratio is likely to have better reliability than the individual joints (280). The progressive onset of overuse injuries indicates that the alterations in loading to the injured tissue are not large but are sufficient to cause degeneration of the tissue with sufficient time. Therefore, any changes in movement patterns are expected to be relatively small. Very large populations need to be studied prospectively in order for conclusive answers regarding injury risk to be gained. It should also be noted that by using intention to treat analysis, a number of athletes that were included in the Uninjured group could have developed Achilles tendon injuries during the study period but were lost to follow-up. Injury questionnaires were emailed out monthly, however variable numbers of completed questionnaires were received from the athletes. This impacts the magnitude of the effect size. Due to the requirement of no lower limb injuries and no previous Achilles injury in the Uninjured group, the control group size was limited. Therefore, it was decided to use the unilateral limb rather than a randomly selected limb in the analysis in order to maximise the number of control limbs available for the analysis. This approach did not account for the effects of leg dominance. Further research is required with a larger prospective population over a longer time period, in order to gain greater numbers in both the injured and control groups.

Practical recommendations

Based on the evidence presented it is recommended that treatment of Achilles tendon injuries should rely less on slow eccentric exercises which could lead to stretching of the calf muscle or tendon. Rehabilitation should focus on more dynamic eccentric movements which are closer to the dynamics of running and are likely to strengthen the tendon and muscles within the load and lengths encountered in running. Training in an environment that promotes increased knee stiffness should be minimised or avoided in those who have been injured and those individuals who run with a stiff knee gait as this could emphasise the knee/ankle stiffness imbalance. This includes running on soft surfaces such as sand and track, in highly cushioned shoes and paces close to race pace. Screening for strength imbalances at the knee and ankle may provide insight into why the knee to ankle ratio is high in these athletes allowing for rehabilitation of this variable. Gait retraining may be useful in stabilising the knee to ankle ratio, focusing on softening the knee during landing.

Conclusions

The difference between knee and ankle stiffness, measured as the k_{knee}/k_{ankle} ratio could identify those at risk of developing Achilles tendon injuries or reoccurrence of an Achilles injury. Therefore, lower limb stiffness may be a useful screening tool. Ankle stiffness appears to be decreased in athletes who have had previous Achilles tendon injuries and this could contribute to the reoccurring nature of the injury. Changes to treatment may be required focusing on correcting the knee ankle balance.

CHAPTER 10

DISCUSSION AND CONCLUSIONS

The aim of the PhD research was to further understand the biomechanical risk factors for Achilles tendon injury. Outcomes of the research were envisaged to later help develop a preventative intervention.

As the PhD progressed, it became evident that the traditional approach to injury risk factor analysis failed to produce conclusive answers. Not only do many of the retrospective studies target overuse injuries in general (2, 5, 8, 9, 98, 125, 326) but the high variability associated with measuring isolated movements of joints result in unclear results (41, 128, 130, 132-135). Overuse injuries at the knee are likely to have a different mechanism of injury than overuse injuries at the Achilles tendon despite both being brought on by running. Therefore in order to gain a better understanding of the mechanisms of injury, epidemiology and risk factor studies need to be more specific regarding injury type. However, it is acknowledged that such research requires large participant numbers. An alternative approach is to dissect the potentially injurious movement into its component parts and compare these between injured and non-injured individuals. However movement is variable with variability increasing the more focused a measurement becomes (327, 328).

The slow onset of overuse injuries suggests that differences in movement between athletes that will become injured and athletes that will remain healthy will be small. It is agreed that overuse injuries are likely to be multifactorial in nature with the accumulation of a number of otherwise innocuous contributors resulting in overloading of the tissue in question (116, 286). Therefore, it is likely that small differences in the component movements of a task will be masked by the variability of the group. Analysis of variability of a movement rather than the outcome movement itself has recently begun to be utilised in order to try and address this problem (79, 329, 330).

In the process of acquiring a skill an individual progressively unlocks more degrees of freedom resulting in high coordinative variability but low endpoint variability (160, 169). It is likely that overuse injuries exhibit a similar hierarchy of variability with many small potentially injurious risk factors coming together in different combinations to produce the final injury endpoint. The injury is the same however the route by which the injury developed may be quite varied. As a result, risk factor analysis of the small component movements are unlikely to show significant or clear differences from the uninjured population.

A single measurement of the movement pattern or movement coordination may therefore illuminate the process leading to an injury endpoint. The factors contributing to the injurious movement pattern or coordination can then be investigated to determine the possible routes by which a particular injury may occur. While this process of analysis does not provide any quick answers to the overuse injury problem it may help to direct future research and enable the development of targeted intervention programs focusing on an athlete’s unique movement profile.

The Van Mechelen (23) and Finch (24) injury prevention development frameworks highlighted the steps believed necessary in developing preventative interventions (Figure 10.1).

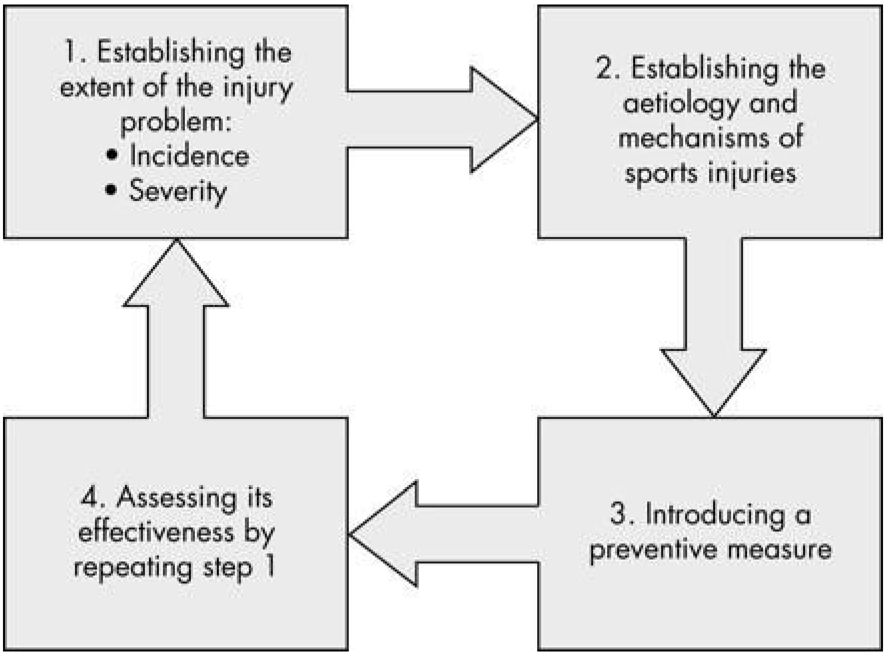

Figure 10.1. Van Mechlen's et al. (23) 'sequence for injury prevention'

The first step in the model is identifying the extent of the problem in terms of incidence and severity. While there have been a number of studies on triathlon injuries (2-12, 27, 28, 97, 331, 332), a lack of consensus on injury definition and reporting of location made the picture unclear (7). Only the work by Vleck et al. (15, 16, 18) reported Achilles tendon injuries directly. Evidence from British triathletes in the 1990's indicated that Achilles tendon injuries had a high prevalence in Olympic distance athletes but were also a problem for the longer distances (16). When ranked by severity based on number of training days lost, only lower back and neck injuries were worse (16). While anecdotal reports were that Achilles injuries were problematic in New Zealand athletes and the media supported this, no formal injury assessment of New Zealand triathletes has been completed in recent years.

Section 1 of the thesis aimed to establishing the extent of the problem via injury data analysis and literature reviews.

Chapter 2 provided epidemiological data for lower limb overuse injuries in New Zealand high performance triathletes. Using the injury data collected by the New Zealand Academy of Sport (NZAS) and then High Performance Sport New Zealand (HPSNZ) from 2007 to 2012, retrospective analysis of injury prevalence was conducted. Fifty-two injuries were reported for 67 athletes over the six year period. Lower leg injuries, particularly calf (17%) and Achilles tendon (17%) injuries were problematic in New Zealand High Performance athletes. Knee (15%) and upper leg (15%) injuries also had a high prevalence. Injuries were primarily attributed to running (85%) and incidence (69 per 100 athletes) was higher in 2011 (a pre-Olympic year).

These results confirmed what was found in the British athletes (16) in terms of Achilles tendon injuries being the most frequent and severe. An improvement in injury surveillance of the New Zealand high performance triathlete has been underway since 2012. Preliminary results indicate that 43% (n=16) of injuries in the period November 2012-Novemeber 2013 were overuse injuries. Of these three (19%) were tendon injuries (location unspecified), 19% were shin pain and 19% were stress fractures. Patellarfemoral joint pain (knee injuries) accounted for two (12.5%) of total overuse injuries. Overuse injuries accounted for the most training days lost (70%, 756 days) however tendon injuries only accounted for 9% (67 days) of this total. Knee injuries (37%) and shin pain (35%) accounted for the most days lost. Overall, the results reflect a similar picture to the longer (2007-2012) retrospective surveillance although numbers were too small to be able to make clear conclusions from the most recent data. The severity of the tendon injuries was less than reported by Vleck et al. (16) however with an ongoing injury such as Achilles tendon injuries, it is expected that the number of training days lost would accumulate with longer surveillance. Investigating preventative interventions would therefore have potential benefit for the sport and triathletes.

Step two of the Van Mechelen (23) model is establishing the cause and mechanism of injury. A literature review was conducted in order to generate an understanding of the potential risk factors for Achilles tendon injuries in running athletes

It was apparent from the results of the review in chapter 3 [Achilles Tendon Injury Risk Factors Associated with Running (167)] that while many risk factors had been identified, very few of these risk factors showed clear association with Achilles injury in running athletes. Five risk factors were clear. Increasing braking force showed a large effect size for increased injury risk. Peak vertical force and high arches had very large association with decreased injury risk. Increasing surface stiffness and propulsive force also showed smaller associations with decreased injury risk. Other notable results from individual studies indicated that males over 35 years of age were more at risk but females did not show similar risk (98). The difference between training and racing pace appeared to be important, with injured athletes reporting a smaller difference between the two running paces than uninjured athletes (136).

The large number of risk factors that showed small, but unclear effect sizes supported the theory that injuries, particularly overuse injuries were multifactorial in nature (116, 286, 330). From here the focus of the thesis shifted to approaching injury risk from a different angle, looking at movement patterns and movement coordination rather than the individual components of the movement.

Lower body stiffness has been used to model running gait and has been predicted to be important in injury development (80, 148, 333). The association between tendon stiffness has been investigated in army recruits (139) without clear results. Leg stiffness was found to be significantly higher in athletes with Achilles tendon injuries while ankle joint stiffness was lower (137). Stiffness was the only risk factor identified which incorporated multiple tissues and joints, therefore give a more integrated view of how the joints, muscles and tendons work together to absorb the load of landing from one step to another (80). Lower limb stiffness might provide a measure which represents the effects of many of the previously identified risk factors. However, it was unclear whether the identified risk factors altered stiffness, in what direction and to what extent.

Since the review of literature was conducted for the thesis and submitted for publication, a one year prospective study has since been published (334). Ten runners out of 142 developed Achilles tendon injuries and their pre-injury movement was assessed against ten uninjured runners matched for age, sex, height and weight. Decreased isometric knee flexor strength and abnormal sagittal knee and ankle kinematics were reported in the group that developed an Achilles tendon injury. Abnormal kinematics included lower maximum ankle dorsiflexion and greater maximum rearfoot eversion and reduced maximal knee flexion with more extended knee at contact. No differences in timing, range of motion and maximal joint velocities were found. It was suggested that a combination of these differences with the increased load of speed training sessions led to the injury in these recreation runners. A more extended knee configuration at contact and reduced knee flexion peak suggests a stiffer knee and therefore a stiffer leg configuration in individuals that developed Achilles tendon injuries.

Review of the literature, reported in chapter 4 [Stiffness as a risk factor for Achilles tendon injury in triathletes and other running athletes: Systematic review], using the risk factors identified in chapter 3 was conducted to determine whether Achilles tendon injury risk factors altered lower body stiffness measures. The results were difficult to interpret due to the use of running and hopping, different methods for estimating stiffness and a wide variety of levels of change in the variables of interest. The trend appeared to suggest that of those risk factors that had been assessed, many of them were associated with increases in at least one of the stiffness measurements. However, some variables that were protective for Achilles tendon injuries, increased propulsive force and vertical force and increased arch height (167) were also shown to increase lower body stiffness measures (149, 175, 176, 178). Pronation is widely believed to be a risk factor for Achilles tendon injuries, however the analysis of different components of the movement showed very diverse effects for injury risk (167). A single study investigated pronation movement on stiffness and found leg stiffness to be reduced (217). The results were not conclusive but did suggest that stiffness as a risk factor for Achilles injury should be investigated further.

Section 2 of the thesis aimed to establish a measure of lower limb stiffness for potential athlete screening tool development.

Based on the results of the literature reviews, stiffness was investigated further as a potential injury risk factor. Review of the stiffness literature showed many methods for measuring and calculating stiffness. Stiffness measures that were in most common use and were hypothesised to have the most relevance for running were utilised for chapter 5.

Chapter 5 provided a comparison of methods for quantifying stiffness and their reliability in triathletes. While vertical and leg stiffness have previously been shown to have good reliability (253, 335), the individual joints due to their greater variability gave poor reliability for both hopping and overground running (242). Hopping is often used as a surrogate for running when testing stiffness because of the reduced space requirements and ability to assess multiple contacts. Hopping is a cyclic movement with a vertical centre of mass trajectory not unlike running (336). Both are termed ‘bouncing gait’. However, how well hopping stiffness correlates to running stiffness had not been reported.

Confounding the issue of how to measure stiffness further is the multiple methods of calculating the different stiffness measures (236, 239). Therefore, a number of different stiffness calculations for vertical, leg and joint stiffness were conducted for both running and hopping by 75 triathletes. Reliability was assessed for all measurements along with comparisons between the hopping and running results. Both the dynamic and time methods for estimating vertical and leg stiffness had good reliability. The use of direct measurements of leg compression, kleg/true, was less reliable. Using a modelled hip joint centre was better than measuring hip joint location from a trochanter marker. The time method was carried forward in all subsequent analysis due to its good reliability and best correlations with measurements of knee and ankle joint stiffness. The time method was also ideal in that analysis required only contact time and flight time making the equipment requirements minimal (contact mat or video). Ankle joint stiffness had acceptable reliability however the knee and hip were moderate to poor. The different joints of the lower limb work together to produce movement of the leg (274). Therefore, a change at the ankle would lead to adjustments at the knee and possibly hip. Analysis of the joints working as a unit rather than isolated should therefore reduce the variability of the measurement. It was proposed to use a combination of the joints as the sum of all three joints, sum of hip and knee and sum of knee and ankle. The combined knee and ankle gave good overall reliability while the combined hip and knee gave moderate overall reliability. The combined knee and ankle stiffness resulted in the best correlation with leg stiffness suggesting that the knee and ankle were the key joints for modifying leg stiffness during the first half of stance with the knee playing the largest role. The hip appeared to have the least influence over leg stiffness during stance.

Stiffness during hopping was generally not well correlated with stiffness during running. Hopping frequency was constrained to 2.2 Hz (reported natural hopping frequency) (196, 241) because frequency was shown to be important in modifying stiffness measures. Running however generally has a frequency closer to 1.5 Hz (246). Hopping stiffness may therefore be correlated with running stiffness as long as the hopping frequency is matched to the runners stride rate. Further investigation of the effects of frequency of movement and type of movement on lower limb stiffness measures is required.

The third section of the thesis examined how lower limb stiffness changed with different task constraints. Chapter 6 established that lower limb stiffness is affected by running pace in triathletes. In order for lower limb stiffness to be useful in identifying athletes at risk of developing Achilles tendon injuries understanding how different aspects of training influence stiffness and injury risk is important. In the risk factor review (167) a lack of difference between training pace and race pace was found to be associated with increased risk of Achilles tendon injury (136). Vertical stiffness and joint stiffness were found to be increased with running velocity (180, 182, 183, 215). However most of the results were unclear (279). Few studies covered the range of running speeds encountered by the triathlon population studied with only two studies looking directly at the effects of discrete changes in running velocity and measures of lower limb stiffness (180, 215) and another looking at percentages of maximal sprinting velocity (183).

Seventy-five elite or competitive age group triathletes were measured for stiffness at four to five running paces. The majority of athletes were unable to complete two minutes at 3.5 min/km and therefore this pace was not analysed further. Unfortunately the lack of understanding of stiffness variables at this faster pace limits carry over to the high performance Olympic distance athletes who race at close to this pace. Further studies need to be conducted using smaller pace progressions over the faster pace ranges to facilitate understanding of how stiffness changes.

It was decided to use pace rather than velocity as the variable for running speed. Pace is the common measure used by triathletes and coaches and therefore has more ecological validity as a potential variable to consider in a movement screening tool. However, in our study, using even increments in pace resulted in uneven increments in velocity. While this could be a limitation to the study it also produced some unexpected interesting results.

Increased running pace was associated with increased vertical, knee and ankle stiffness. Hip and leg stiffness were relatively unaffected by changes in pace. Different sized velocity increments gave varying effect size magnitudes. It was not a clear linear relationship as expected, rather a polynomial relationship. The starting pace also determined which measurements were increased and to what degree.

As a result of this study it was hypothesised that this variable pattern of stiffness change was related to the gait movement pattern and how the changes in pace were achieved. The relatively slow running pace of 5.5 min/km may have resulted in a shorter stride length and therefore a steeper angle of attack. It is speculated that the shorter stride lengths were set up by the hip during flight with reduced hip flexion, and resulting in higher leg stiffness. Increasing the pace resulted in small decreases in leg stiffness which based on the dynamics of the ‘spring-mass’ model would be the result of using a shallower angle of attack and therefore a greater leg swing angle (θ) (191). The decrease in leg stiffness was also associated with a smaller than predicted knee and ankle stiffness increase. Increasing knee and ankle stiffness would be more associated with reducing stride rate than increasing stride length. The knee and ankle did not increase stiffness simultaneously. The ankle stiffness appeared to increase first for smaller pace changes with the knee stiffness adjusting only when larger increases in lower limb stiffness were required. The different role of the joints in pace adjustments were therefore apparent. It was recommended that athletes utilise a wide range of paces during training in order to distribute the load over the different joints and tissues.

Chapter 7 examined the reliability and variability of stiffness measures with changes in running velocity. The effect of velocity on the different measures of stiffness showed that the magnitude of the task change affected which stiffness variable and to what degree the variable was changed. Being able to tailor athlete testing to fit the requirements of the athlete’s performance level and distance specialisation is important when identifying individual athletes that require preventative intervention. Therefore, it was important to establish reliability of the stiffness measurements with increasing pace.

Twelve athletes were tested using a test-retest procedure for the four running paces (5.5, 5.0, 4.5 and 4.0 min/km). Reliability was constant for vertical and leg stiffness over the range of paces covered. Combining the knee and ankle stiffness allowed for acceptable reliability over the entire pace range.

Variability of movement has been suggested to be associated with injury risk. Low variability in a movement could result in consistent loading to a small range of tissues resulting in overloading of these tissues (79, 337). However, too much variability may result in steps that are outside the physiological safe range and could also lead to progressive build-up of damage (337). Therefore understanding how variability changed with increasing pace was important from an injury point of view. Movement patterns leading to overuse injuries are likely to differ from safe movement patterns by only small amounts. Therefore high variability in the measurement may result in differences which are lost because of large confidence intervals.

Between subject variability measured as the coefficient of variation (CV%) remained relatively constant over the range of paces measured suggesting that athletes tended to use the same strategies to increase running pace. If the starting pace and the magnitude of the velocity increase determines the strategy by which pace is increased and therefore stiffness modified then we would expect the between subject variability to be a reflection of the natural population variability and show little influence from changing pace. In which case, individuals that are outliers from this general pattern of stiffness adjustment may be more at risk of injury. Alternatively, if every athlete has an individual strategy for adjusting pace then a large amount of scatter would occur and a linear trend with little correlation to pace may also result.

Within subject variability of 10 consecutive steps demonstrated a slight 'U-shaped' distribution with increasing pace. Further investigation regarding within-subject variability and preferred pace is required. Long range correlations indicated that, at the preferred pace, steps distant from one another show less correlation to each other than at faster or slower paces (338). However, only 10 steps were used in our analysis compared to the hundreds used for detrended fluctuation analysis.

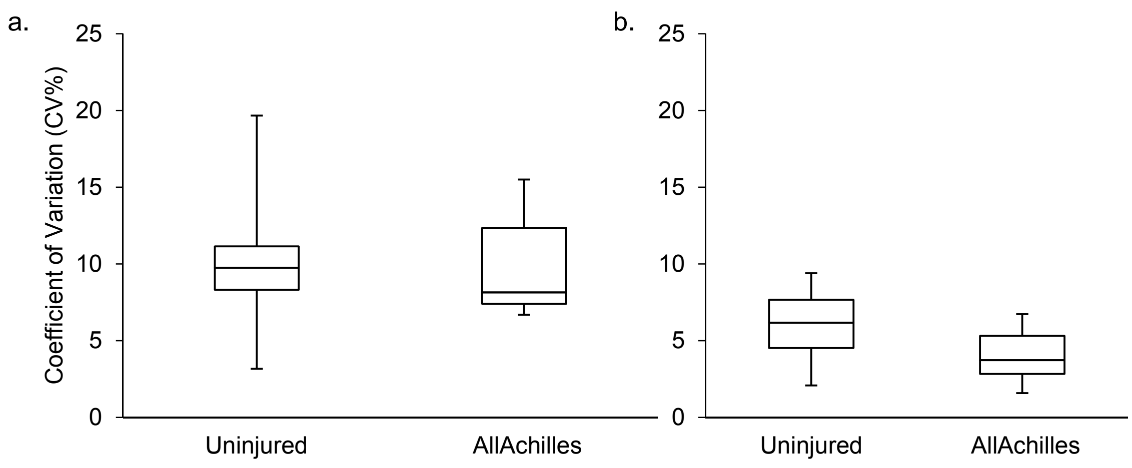

Figure 10.2: Within-athlete knee a). and ankle b). stiffness variability between the Uninjured and the AllAchilles groups

Comparison of the step-to-step variability between the Uninjured athletes from Chapter 9 [Lower limb stiffness for the prediction of Achilles tendon injuries in triathletes: A prospective study] showed that the spread of variability for the Uninjured group was greater (Figure 10.2, a). The knee stiffness variability for those athletes that developed an Achilles tendon injury during the surveillance year fitted within the variability of the Uninjured group. The ankle stiffness variability of the group that developed an Achilles injury however, was lower than for the Uninjured group (Figure 10.2, b). The within subject variability differences between the groups lends some support to the concept that lower movement variability is associated with increased risk of injury (155, 337). Further investigation on a larger population is required.

Chapter 8 examined the influence of prior cycling on lower limb stiffness in triathletes (i.e., the transition). Triathletes are unique when it comes to assessing overuse injury because they train for excellence in three disciplines. The run has become the dominant discipline in determining race outcomes at all distances. Proficiency at all three disciplines is needed as the race can be lost on the swim and the bike. Triathlon was initially thought to reduce the injury risk because loading was more diverse. However, incorporating training sessions for two or even three of the disciplines into a single day reduces the recovery time. Another consideration is the need to rapidly change from one discipline to another. With the run being most important in determining race outcome, athletes who can adapt quickly to running following cycling are more likely to be successful. However, the transition from cycling to running appears to be more extreme compared to the swim to run transition. Physiological and biomechanical changes have been reported for the cycle to run transition when compared to isolated running (214, 224, 225, 228, 230, 303, 310, 315, 339), however the biomechanical changes are controversial.

It is believed that the period of adaption when transitioning from cycling to running is related to an increased risk of injury (228), however there is no evidence that conclusively supports this. Sagittal plane kinematics following 30 minutes of cycling in the ‘aero’ position showed increased anterior pelvic tilt, increased hip flexion and decreased hip extension (228). Such changes are commonly associated with increased running pace. With no increase in running pace, it was suggested that increased loading to the lower back and lower extremities could occur increasing injury risk.

In our study the effect of 30 minutes of self-paced cycling appeared to have little effect on the stiffness measurements. A small to moderate increase in leg and ankle stiffness compared to isolated running were seen in the first minute of transition running however the results were not definite.

Scatter plot analysis of the absolute changes that occurred in the first five minutes of transition running compared to isolated running, indicated that while most triathletes had very little change in the stiffness measures a few athletes did show altered movement patterns. In triathletes that showed changes in stiffness, leg and vertical stiffness were generally increased, while there were two different changes observed for the knee and ankle. Some triathletes showed increased knee and increased ankle stiffness while others showed decreased knee with increased ankle stiffness.

These three chapters provided information regarding how stiffness and stiffness variability was altered by changing the nature of the task or environment constraints. However, they do not provide any evidence as to whether stiffness is associated with injury risk and in what way. Without prospective studies we cannot assign causation to any risk factors. Therefore the thesis culminated in a 1-year prospective injury study to determine which, if any, measures of stiffness may be useful in identifying triathletes at risk of developing Achilles tendon injuries.

The fourth section of the thesis examined whether stiffness could help identify injury risk.

Chapter 9 reports the prospective study of lower limb stiffness for the prediction of Achilles tendon injuries in triathletes.

Prospective injury, intention to treat analysis, over one year was conducted on 75 triathletes with stiffness measurements conducted at the beginning of the one year surveillance period. Eight Achilles tendon injuries were reported in seven athletes of which four athletes had had previous Achilles tendon injuries (PriorAchilles) and three experienced their first Achilles injury (FirstAchilles). Control athletes were those that did not report any lower body injuries in the surveillance period (Uninjured). A subgroup of athletes that had had prior Achilles injuries but did not report any lower body injury in the surveillance period was also included in the analysis (PriorUninjured).

Forest plots of the average effect sizes as well as the effect sizes for the individual paces were produced for the comparisons PriorUninjured v Uninjured, PriorAchilles v Uninjured and FirstAchilles v Uninjured. Ankle stiffness was reduced in all athletes who had had an Achilles tendon injury previously as well as the group which would go on to develop their first Achilles injury. The decrease in ankle stiffness in the PriorAchilles group compared to the uninjured group was greater than in the FirstAchilles group.

It is suggested that the Alfredson protocol used in rehabilitation of Achilles injuries and often continued by the athlete whenever pain reappears may cause this decreased stiffness and could increase the chance of reinjury. Leg stiffness was higher in both the Achilles injury groups compared to the uninjured triathletes and knee stiffness was higher in the group who developed their first Achilles tendon.

The pattern of the effect sizes for the different groups led to post-hoc analysis of a new measure, the knee-ankle stiffness ratio. The results showed that this measure was the best measurement for predicting injury, both first Achilles injury and reoccurrence of Achilles injury. Individuals who went on to develop an Achilles tendon injury during the surveillance year had greater knee-ankle stiffness ratios compared to uninjured. However, the difference in ratio was not apparent in the previously injured but not reinjured group. The knee-ankle stiffness ratio shows that the risk of developing an Achilles tendon injury is increased if knee stiffness is substantially greater than ankle stiffness.

Plotting the effect sizes for the injury analysis provided a visual aid to the interpretation of the results allowing rapid pattern recognition. While looking at the results of the comparisons between each of the injury subgroups and the uninjured individuals I noted that while none of the subgroups had notably similar results, in terms of the absolute effect sizes, the two groups that developed an Achilles tendon injury during the surveillance periods had a similar pattern. The knee and ankle stiffness effect sizes were approximately the same distance apart but were shifted further to the right for the FirstAchilles group. The PriorUninjured group however did not have this difference between the effect sizes of the knee and ankle stiffness. I began to think that maybe it was not the absolute stiffness value that was therefore important, rather the ratio between the knee and the ankle that might provide insight into injury risk. While the idea of using the relationship between the knee and ankle as a measure of lower limb function was prominent in the thesis from the outset, this was purely in the form of summation.

Based on these results the effect of velocity and transition on the new knee-ankle ratio has been assessed. Figure 10.3 shows the effect of increasing running velocity on the knee/ankle stiffness ratio. Changing pace, regardless of the size of the velocity increment had no effect on the knee-ankle ratio measurement. Therefore, training pace does not appear to be associated with increased Achilles tendon injury based on this measure.

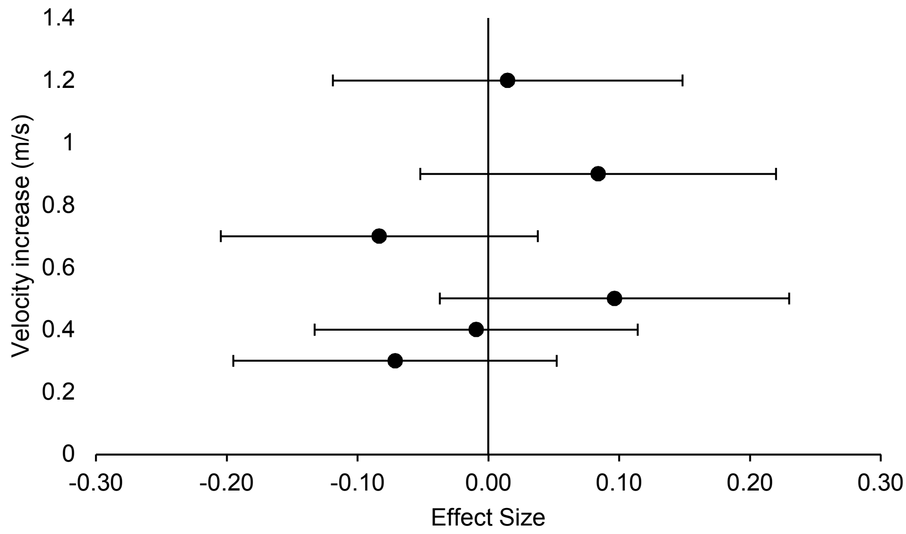

Figure 10.3: Effect of increasing pace on the knee/ankle stiffness ratio

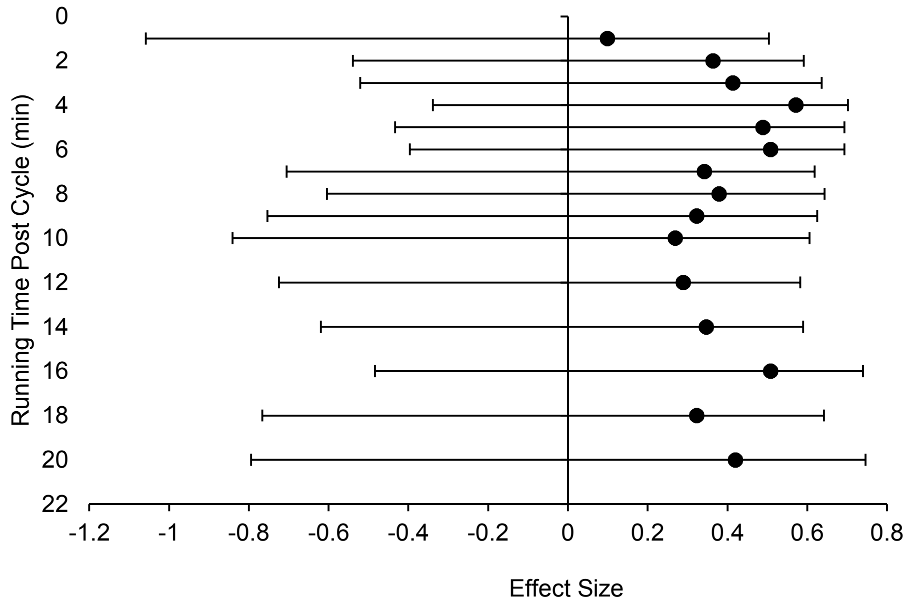

Figure 10.4: Effect of prior cycling on the knee/ankle stiffness ratio during running

Figure 10.4 shows the change in the knee/ankle stiffness ratio over the 20 minutes of running following a 30 minute self-paced cycle with respect to the isolated run. The results were unclear, however it is possible that previous cycling caused a small decrease in the knee-ankle stiffness ratio. The decrease is more likely to occur after the first minute and therefore may be more fatigue related than coordination related. A decrease in the knee-ankle stiffness ratio was not associated with increased Achilles tendon injury risk. The scatter plot showed that a small number of athletes showed decreased knee stiffness and increasing ankle stiffness when running following cycling. This would cause the observed decrease in the knee-ankle stiffness ratio and would be associated with running with a “softer” knee (i.e. greater knee flexion at contact and greater knee flexion range of motion). This would reduce the load on the Achilles tendon through reduced gastrocnemius force and may be protective for the Achilles tendon.

The knee-ankle stiffness ratio did not appear to be increased as a result of increasing pace or running following cycling. However, analysis of how the injury subgroup responded to these changes in task constraints should be conducted, in order to determine whether the tasks increased injury risk.

Maintaining the balance and coordination of the different joints is a delicate balancing act between agonist and antagonist muscles. Biarticular muscles play an integral role in maintaining this balance. The biarticular gastrocnemius contributes fibres to the Achilles tendon both from the lateral and medial muscle bellies and controls plantarflexion at the ankle and also knee flexion. As a result the position of the two joints can alter the activity of the gastrocnemius muscle (111, 340). When the ankle is plantarflexed and the knee flexed, both the gastrocnemius and the soleus are acting as agonists however shorter fascicle lengths of the gastrocnemius results in active insufficiency (111, 340). In this case running with a mid to fore foot strike may increase this effect, although with only small knee flexion the effect would be minor. With plantarflexion and knee extension, as in the propulsive phase of running reciprocal inhibition occurs. With dorsiflexion and knee extension passive insufficiency occurs. All of these alterations in muscle activity occur as part of the physiological balancing act to maintain balance and coordination during movement. A high knee stiffness compared to ankle stiffness would suggest minimal knee flexion with possible excessive dorsiflexion. Perhaps it is a loss of the normal balancing between gastrocnemius and soleus activity which leads to Achilles tendon injury. Whether the mechanism of tissue damage is through shearing or tensile loading, altering the contribution of the muscles of the triceps surae complex would lead to uneven loading through the tendon and could result in microscopic rupture damage.

Limitations

By utilising an endpoint measurement of movement rather than the component movements to analyse injury risk we hope to have minimised the problem of multiple biomechanical routes to injury and unclear results due to high movement variability. However, there are a number of limitations to this approach. Most notably we are left with more questions than answers. We have shown that a high knee to stiffness ankle ratio can possibly predict whether an individual will develop an Achilles tendon injury or suffer from a reoccurrence. But we are left to only speculate regarding the cause of the high knee to ankle stiffness ratio. We have shown that stiffness adjustments are dependent on the starting pace as well as the magnitude of the running velocity increase. The knee and ankle do not adjust together rather work as separate units depending on the magnitude of the stiffness change required. However, the gait parameters and possible points of intervention in order to change a potentially harmful knee to ankle stiffness ratio remain unclear. Based on previous research it is proposed that the stride length and stride rate characteristics may provide useful information. Further research into these variables and their relationship to the stiffness changes observed. We have seen that transitioning from cycling to running results in individual responses. Some individuals responded with increased ankle stiffness and decreased knee stiffness which following the prospective results would give a lower knee to stiffness ankle ratio and therefore reduce the risk of Achilles tendon injuries. However, does this imbalance lead to other injury possibilities? Again it is unclear what leads to the different responses in the different athletes. The spatial and temporal gait characteristics need to be assessed and compared with the different stiffness responses. Changes in gait parameters following cycling has performance implications that also need to be investigated.

With all the questions that have come to light there is plenty of future research to be carried out. We may be able to discover the different biomechanical influences leading to Achilles tendon injuries and be able to tailor interventions to fit the athlete by examining stiffness further.

Future directions

While the research has resulted in some interesting developments in the understanding of how different task constraints alter the stiffness control of gait, many questions have been generated as a result. Future research should investigate the relationship between sagittal plane joint mechanics and stiffness changes with increasing pace in order to confirm the hypothesis of differing joint responsibilities depending on the initial running pace and the magnitude of the pace change. The effect of pace changes should also be investigated over a wider range of paces with smaller velocity increments in order to get a more in depth understanding of how the stiffness control of gait changes. Analysis should also be conducted in a subgroup of athletes who demonstrate the elevated knee-ankle ratio measure that was shown to be associated with increased risk of Achilles tendon injury in order to determine if these athletes respond differently to the larger group and therefore whether increasing pace increases injury risk. Similar research is warranted for running following cycling.

The variability of the different stiffness measures from step to step within an athlete and compared to the variability between athletes may help to understand how stiffness is utilised to stabilise gait. It may also provide insight into the mechanism of other lower limb injuries.

The exact cause of the increased knee-ankle ratio in triathletes should be investigated. Is it a strength deficiency or imbalance? This is a potential explanation given the reduced isometric knee flexion strength reported in athletes that developed Achilles tendon injuries reported by Hein et al. (2014). Is it a movement, coordination problem that requires gait retraining? Understanding this will enable the development of preventative interventions.

Injury numbers were small for our study, therefore larger prospective studies over a longer time period are required to confirm the results and enable the determination of a knee-ankle stiffness ratio level above which an athlete should be flagged as being at risk. Studies should also be conducted in other athletes who show high prevalence of Achilles tendon injuries in order to determine if they too show increased knee-ankle stiffness ratio.

Once all these questions have been answered, the development and introduction of a preventative intervention can begin with assessment of risk reduction. Only then will causation be conclusively attributed to a change in the balance between knee and ankle stiffness.

Recommendations

Based on the research it is recommended that all athletes in the high performance squad should have leg stiffness measured over a variety of velocities for running. A leg stiffness greater than 0.16 kN/m/kg may be an indicator of Achilles injury risk and these athletes should undergo more in depth analysis. Knee and ankle stiffness should be assessed with a knee/ankle stiffness ratio of more than 1.10 being used as a flag for high Achilles injury risk. Individuals who are returning to sport following an Achilles injury should have the knee to ankle stiffness ratio assessed. A ratio of 1.00 or lower is ideal in these athletes before returning to competition, as an indicator of reduced risk of reoccurrence and therefore good rehabilitation.

As we are yet to develop a preventative intervention, a number of options are available in treating at-risk athletes. Strength testing looking at imbalances between the knee and ankle control muscles, between the calf and the tibialis anterior muscles and between lower leg and upper leg muscles should be considered and any strength deficits addressed. Deficits in strength may be the result of, or exacerbated by a suboptimal bicycle position or technique. Cycling mechanics analysis should be undertaken. While running on sand was found to be a significant risk factor for Achilles injury from the analysis of literature in chapter 2, it was noted that running on softer surfaces resulted in increased ankle stiffness and decreased knee stiffness from the analysis of literature in chapter 3. Changing the ratio of the joint stiffness in this manner may be beneficial in preventing injury and therefore running on softer surfaces such as track or grass may be preventative.

The foot strike pattern of an individual could be modified to a more forefoot strike which has been shown to increase ankle stiffness and decrease knee stiffness. However, individuals should be aware that changing strike pattern has a risk of injury if not progressed slowly and may lead to initial performance decrements. Individuals should also be advised on focusing on running with increased knee flexion particularly when running down hills.

Conclusions

The research aimed to increase the understanding of how the biomechanics of running influenced the risk of developing Achilles tendon injuries in triathletes.

The knee-ankle stiffness ratio did not give clear effect sizes between the injured and uninjured athletes. However the number of injured athletes were small and the use of an intention to treat analysis would increase the risk of athletes that developed an Achilles injury being included in the uninjured group (based on injury rates up to two athletes could have been included in the uninjured group). Larger studies should help to clarify this issue.

The knee-ankle stiffness measurement can be achieved in a single measurement session and other injury factors involved in gait analysis can also be assessed at this time. At this stage the measurement is not simple enough to be performed at different locations or in the field as joint stiffness requires modelling of joint moments. Minimum equipment for this is currently 2D video and force data. Leg stiffness also had a small increase in stiffness in the Achilles injury groups compared to uninjured athletes. Leg stiffness can be reliably measured in a number of locations using either video or contact time data. Therefore, leg stiffness may be a useful measure as an initial screen to select athletes that should be assessed with the more complex analysis. Further investigation of this possibility is required.

The stiffness measures were shown to be reliable over a number of different paces and therefore are potentially useful as a screening tool because they can be adapted to the demands of the individual athlete. While the mechanism leading to increased knee-ankle stiffness is not yet known, that is the next step in unravelling the problem that is the Achilles heel.

REFERENCES

1.Andersen CA, Clarsen B, Johansen TV, Engebretsen L. High prevalence of overuse injury among iron-distance triathletes. British Journal of Sports Medicine. 2013;47(13):857-61.

2.Burns J, Keenan A, Redmond AC. Factors associated with triathlon-related overuse injuries. Journal of Orthopaedic and Sports Physical Therapy. 2003;33(4):177-84.

3.Clements K, Yates B, Curran M. The prevalence of chronic knee injury in triathletes. British Journal of Sports Medicine. 1999;33(3):214-6.

4.Collins K, Wagner M, Peterson K, Storey M. Overuse injuries in triathletes. A study of the 1986 Seafair Triathlon. The American Journal of Sports Medicine. 1989;17(5):675-80.

5.Egermann M, Brocai D, Lill CA, Schmitt H. Analysis of injuries in long-distance triathletes. International Journal of Sports Medicine. 2003;24(4):271-6.

6.Egermann M, Schmitt H. Injuries in triathlon - Analysis of 656 Ironman-athletes. (Abstract). International Journal of Sports Medicine. 2002;23(S2):S104-S.

7.Gosling CM, Gabbe BJ, Forbes AB. Triathlon related musculoskeletal injuries: The status of injury prevention knowledge. Journal of Science and Medicine in Sport. 2008;11(4):396-406.

8.Korkia PK, Tunstall Pedoe DS, Maffulli N. An epidemiological investigation of training and injury patterns in British triathletes. British Journal of Sports Medicine. 1994;28(3):191-6.

9.Migliorini S. An epidemiological study of overuse injuries in Italian national triathletes in the period 1987-1990. Journal of Sports Traumatology and Related Research. 1991;13(4):197-206.

10.Migliorini S. The triathlon: Acute and overuse injuries. Journal of Sports Traumatology and Related Research. 2000;22(4):186-95.

11.Migliorini S. Risk factors and injury mechanism in triathlon. Journal of Human Sport and Exercise. 2011;6(2):309-14.

12.O'Toole ML, Hiller DB, Smith RA, Sisk TD. Overuse injuries in ultraendurance triathletes. The American Journal of Sports Medicine. 1989;17(4):514-8.

13.Shaw T, Howat P, Trainor M, Maycock B. Training patterns and sports injuries in triathletes. Journal of Science and Medicine in Sport. 2004;7(4):446-50.

14.Vleck V, Alves FB. Triathlon injury review. British Journal of Sports Medicine. 2011;45(4):382-3.

15.Vleck V, Garbutt G. Overuse injury prevalence and associated risk factors in male national squad and club triathletes training for the 1,5 km, 40 km, 10 km, triathlon. Journal of Sports Sciences. 1998;16(1):66.

16.Vleck VE, Bentley DJ, Millet GP, Cochrane T. Triathlon event distance specialization: Training and injury effects. The Journal of Strength and Conditioning Research. 2010;24(1):30-6.

17.Vleck VE, Garbutt G, editors. A comparison of training and injury characteristics of British male elite, development squad, and club level triathletes. First Annual Congress, Frontiers in Sport Science, the European Perspective; 1996; Nice, France.

18.Vleck VE, Garbutt G. Injury and training characteristics of male elite, development squad, and club triathletes International Journal of Sports Medicine. 1998;19(1):38-42.

19.Longo UG, Ronga M, Maffulli N. Achilles tendinopathy. Sports Medicine and Arthroscopy Review. 2009;17(2):112-26.

20.Williams JGP. Achilles tendon lesions in sport. Sports Medicine. 1986;3(2):114-35.

21.Silbernagel KG, Thomee R, Eriksson BI, Karlsson J. Full symptomatic recovery does not ensure full recovery of muscle-tendon function in patients with Achilles tendinopathy. British Journal of Sports Medicine. 2007;41(4):276-80.

22.Levy C, Kolin E, Berson B. The effect of cross training on injury incidence, duration, and severity (part 2). Sports Medicine Clinics Forum. 1986;3:1-8.

23.van Mechelen W. Running injuries. Sports Medicine. 1992;14(5):320-35.

24.Finch C. A new framework for research leading to sports injury prevention. Journal of Science and Medicine in Sport. 2006;9(1-2):3-9.

25.Vleck V, Alves FB. Cross-training and injury risk in british olympic distance triathletes. British Journal of Sports Medicine. 2011;45(4):382.

26.Manninen J, Kallinen M. Low back pain and other overuse injuries in a group of Japanese triathletes. British Journal of Sports Medicine. 1996;30(2):134-9.

27.Galera O, Gleizes-Cervera S, Pillard F, Rivière D. Prevalence of injury among a sample of French amateur triathletes. Science and Sports. 2009;24(6):288-92.

28.Cipriani DJ, Swartz JD, Hodgson CM. Triathlon and the multisport athlete. Journal of Orthopaedic and Sports Physical Therapy. 1998;27(1):42-50.

29.Roberts TJ, Konow N. How tendons buffer energy dissipation by muscle. Exercise and Sport Sciences Reviews. 2013;41(4):186-93.

30.Nickisch F. Anatomy of the Achilles tendon. In: Nunley JA, editor. The Achilles Tendon: Springer New York; 2009. p. 2-16.

31.Shaw H, Benjamin M. Structure–function relationships of entheses in relation to mechanical load and exercise. Scandinavian Journal of Medicine and Science in Sports. 2007;17(4):303-15.

32.Thomopoulos S, Williams GR, Gimbel JA, Favata M, Soslowsky LJ. Variation of biomechanical, structural, and compositional properties along the tendon to bone insertion site. Journal of Orthopaedic Research. 2003;21(3):413-9.

33.Kvist M. Achilles tendon injuries in athletes. Annales Chirurgiae et Gynaecologiae. 1990;80(2):188-201.

34.Schepsis AA, Jones H, Haas AL. Achilles tendon disorders in athletes. The American Journal of Sports Medicine. 2002;30(2):287-305.

35.O'Brien M. The anatomy of the Achilles tendon. Foot and Ankle Clinics. 2005;10(2):225-38.

36.Clegg PD, Strassburg S, Smith RK. Cell phenotypic variation in normal and damaged tendons. International Journal of Experimental Pathology. 2007;88(4):227-35.

37.Kirkendall D, Garrett W. Function and biomechanics of tendons. Scandinavian Journal of Medicine and Science in Sports. 1997;7(2):62-6.

38.Maffulli N, Barrass V, Ewen SW. Light microscopic histology of achilles tendon ruptures. A comparison with unruptured tendons. The American Journal of Sports Medicine. 2000;28(6):857-63.

39.Kannus P. Etiology and pathophysiology of chronic tendon disorders in sports. Scandinavian Journal of Medicine and Science in Sports. 1997;7(2):78-85.

40.Clement DB, Taunton JE, Smart GW. Achilles tendinitis and peritendinitis: Etiology and treatment. The American Journal of Sports Medicine. 1984;12(3):179-84.

41.Donoghue OA, Harrison AJ, Laxton P, Jones RK. Lower limb kinematics of subjects with chronic Achilles tendon injury during running. Research in Sports Medicine. 2008;16(1):23-38.

42.Hreljac A, Marshall RN, Hume PA. Evaluation of lower extremity overuse injury potential in runners. Medicine and Science in Sports and Exercise. 2000;32(9):1635-41.

43.Wyndow N, Cowan SM, Wrigley TV, Crossley KM. Neuromotor control of the lower limb in Achilles tendinopathy: Implications for foot orthotic therapy. Sports Medicine. 2010;40(9):715-27.

44.Wren TAL, Beaupre GS, Carter DR. Tendon and ligament adaptation to exercise, immobilization, and remobilization. Journal of Rehabilitation Research and Development. 2000;37(2):217-24.

45.Cook J, Purdam C. Is compressive load a factor in the development of tendinopathy? British Journal of Sports Medicine. 2012;46(3):163-8.

46.Wren TAL, Yerby SA, Beaupré GS, Carter DR. Mechanical properties of the human achilles tendon. Clinical Biomechanics. 2001;16(3):245-51.

47.Scott SH, Winter DA. Internal forces of chronic running injury sites. Medicine and Science in Sports and Exercise. 1990;22(3):357-69.

48.Komi P, Fukashiro S, Järvinen M. Biomechanical loading of Achilles tendon during normal locomotion. Clinics in Sports Medicine. 1992;11(3):521-31.

49.Kongsgaard M, Nielsen CH, Hegnsvad S, Aagaard P, Magnusson SP. Mechanical properties of the human Achilles tendon, in vivo. Clinical Biomechanics. 2011;26(7):772-7.

50.Lichtwark GA, Wilson A. In vivo mechanical properties of the human Achilles tendon during one-legged hopping. Journal of Experimental Biology. 2005;208(24):4715-25.

51.Hansen P, Aagaard P, Kjaer M, Larsson B, Magnusson SP. Effect of habitual running on human Achilles tendon load-deformation properties and cross-sectional area. Journal of applied physiology. 2003;95(6):2375-80.

52.Tallon C, Maffulli N, Ewen S. Ruptured Achilles tendons are significantly more degenerated than tendinopathic tendons. Medicine and Science in Sports and Exercise. 2001;33(12):1983-90.

53.Maffulli N, Testa V, Capasso G, Ewen SW, Sullo A, Benazzo F, et al. Similar histopathological picture in males with Achilles and patellar tendinopathy. Medicine and Science in Sports and Exercise. 2004;36(9):1470-5.

54.Åström M, Rausing A. Chronic Achilles tendinopathy: A survey of surgical and histopathologic findings. Clinical Orthopaedics and Related Research. 1995;316:151-64.

55.Khan KM, Cook JL, Bonar F, Harcourt P, Åstrom M. Histopathology of common tendinopathies. Sports Medicine. 1999;27(6):393-408.

56.de Mos M, van El B, DeGroot J, Jahr H, van Schie HTM, van Arkel ER, et al. Achilles tendinosis changes in biochemical composition and collagen turnover rate. American Journal of Sports Medicine. 2007;35(9):1549-56.

57.Corps A, Robinson A, Movin T, Costa M, Hazleman B, Riley G. Increased expression of aggrecan and biglycan mRNA in Achilles tendinopathy. Rheumatology. 2006;45(3):291-4.

58.Ireland D, Harrall R, Curry V, Holloway G, Hackney R, Hazleman B, et al. Multiple changes in gene expression in chronic human Achilles tendinopathy. Matrix Biology. 2001;20(3):159-69.

59.Jelinsky SA, Rodeo SA, Li J, Gulotta LV, Archambault JM, Seeherman HJ. Regulation of gene expression in human tendinopathy. BMC Musculoskeletal Disorders. 2011;12(1):86.

60.Sharma P, Maffulli N. Biology of tendon injury: Healing, modeling and remodeling. Journal of Musculoskeletal and Neuronal Interactions. 2006;6(2):181-90.

61.Thornton GM. Changes in mechanical loading lead to tendonspecific alterations in MMP and TIMP expression: influence of stress deprivation and intermittent cyclic hydrostatic compression on rat supraspinatus and Achilles tendons. British Journal of Sports Medicine. 2010;44(10):698-703.

62.Magra M, Maffulli N. Matrix metalloproteases: A role in overuse tendinopathies. British Journal of Sports Medicine. 2005;39(11):789-91.

63.Gardner K, Arnoczky SP, Caballero O, Lavagnino M. The effect of stress-deprivation and cyclic loading on the TIMP/MMP ratio in tendon cells: An in vitro experimental study. Disability and Rehabilitation. 2008;30(20-22):1523-9.

64.Lavagnino M, Arnoczky SP, Egerbacher M, Gardner KL, Burns ME. Isolated fibrillar damage in tendons stimulates local collagenase mRNA expression and protein synthesis. Journal of Biomechanics. 2006;39(13):2355-62.

65.Frost HM. Bone's mechanostat: A 2003 update. The Anatomical Record Part A: Discoveries in Molecular, Cellular and Evolutionary Biology. 2003;275(2):1081-101.

66.Arnoczky SP, Caballero O, Gardner K, Shender MA. Loss of homeostatic strain alters mechanostat “set point” of tendon cells in vitro. Clinical Orthopaedics and Related Research. 2008;466(7):1583-91.

67.Arnoczky SP, Lavagnino M, Egerbacher M. The mechanobiological aetiopathogenesis of tendinopathy: is it the over-stimulation or the under-stimulation of tendon cells? International Journal of Experimental Pathology. 2007;88(4):217-26.

68.Magnusson SP, Narici MV, Maganaris CN, Kjaer M. Human tendon behaviour and adaptation, in vivo. The Journal of Physiology. 2008;586(1):71-81.

69.Screen HRC. Investigating load relaxation mechanics in tendon. Journal of the Mechanical Behavior of Biomedical Materials. 2008;1(1):51-8.

70.Brüggemann G-P, Potthast W, Lersch C, Segesser B. Achilles tendon strain distribution is related to foot and shank kinematics and muscle forces. Journal of Biomechanics. 2007;40(S2):S139.

71.Horgan CO, Murphy JG. Simple shearing of soft biological tissues. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science. 2011;467(2127):760-77.

72.Finni T, Hodgson JA, Lai AM, Edgerton VR, Sinha S. Nonuniform strain of human soleus aponeurosis-tendon complex during submaximal voluntary contractions in vivo. Journal of Applied Physiology. 2003;95(2):829-37.

73.Kawakami Y, Ichinose Y, Fukunaga T. Architectural and functional features of human triceps surae muscles during contraction. Journal of Applied Physiology. 1998;85(2):398-404.

74.Bojsen-Møller J, Hansen P, Aagaard P, Svantesson U, Kjaer M, Magnusson SP. Differential displacement of the human soleus and medial gastrocnemius aponeuroses during isometric plantar flexor contractions in vivo. Journal of Applied Physiology. 2004;97(5):1908-14.

75.Farris DJ, Trewartha G, Polly McGuigan M. Could intra-tendinous hyperthermia during running explain chronic injury of the human Achilles tendon? Journal of Biomechanics. 2011;44(5):822-6.

76.Wilson AM, Goodship AE. Exercise-induced hyperthermia as a possible mechanism for tendon degeneration. Journal of Biomechanics. 1994;27(7):899-905.

77.de Jonge S, van den Berg C, de Vos RJ, van der Heide HJL, Weir A, Verhaar JAN, et al. Incidence of midportion Achilles tendinopathy in the general population. British Journal of Sports Medicine. 2011;45(13):1026-8.

78.Kujala UMMDP, Sarna SP, Kaprio JMDP. Cumulative incidence of Achilles tendon rupture and tendinopathy in male former elite athletes. Clinical Journal of Sport Medicine. 2005;15(3):133-5.

79.Hamill J, Palmer C, Van Emmerik RE. Coordinative variability and overuse injury. Sports Medicine, Arthroscopy, Rehabilitation, Therapy and Technology. 2012;4(1):45.

80.Butler RJ, Crowell III HP, Davis IM. Lower extremity stiffness: Implications for performance and injury. Clinical Biomechanics. 2003;18(6):511-7.

81.Quatman CE. Prediction and prevention of musculoskeletal injury: A paradigm shift in methodology. British Journal of Sports Medicine. 2009;43(14):1100-7.

82.Gosling C, Gabbe B, Forbes A. Coaches' and health professionals' perceptions of injury and injury risk factors in Australian age-group triathletes. Journal of Science and Medicine in Sport. 2009;12(S1):S54.

83.Allison GT, Purdam C. Eccentric loading for Achilles tendinopathy — strengthening or stretching? British Journal of Sports Medicine. 2009;43(4):276-9.

84.Langberg H, Ellingsgaard H, Madsen T, Jansson J, Magnusson SP, Aagaard P, et al. Eccentric rehabilitation exercise increases peritendinous type I collagen synthesis in humans with Achilles tendinosis. Scandinavian Journal of Medicine and Science in Sports. 2007;17(1):61-6.

85.Khan KM, Maffulli N. Tendinopathy: An Achilles' heel for athletes and clinicians. Clinical Journal of Sport Medicine. 1998;8(3):151-4.

86.Sydney litmus test for Debbie Tanner 2011 [updated 05 April]. Available from: http://www.stuff.co.nz.

87.Nationals the next step for Kate McIlroy [press release] 2011 [updated 08 March]. Available from: http://www.stuff.co.nz.

88.Padhiar N, Al-Sayeagh H, Chan O, King J, Maffulli N. Pennation angle of the soleus in patients with unilateral Achilles tendinopathy. Disability and Rehabilitation. 2008;30(20-22):1640-5.

89.King A. Taupo Half: Cameron Brown confident. Rotorua Daily Post. 2011 8 December.

90.TriNZ. Bozzone undergoes successful surgery on achilles Auckland 2011 [updated 2013]. Available from: http://www.triathlon.org.nz/blog/cat/2010_11_other_news_and_releases/post/id1339/.

91.Williams MM, Hawley JA, Black R, Freke M, Simms K. Injuries amongst competitive triathletes. Physiotherapy in Sport. 1988;11(3):13-5.

92.Hausswirth C, Vallier JM, Lehenaff D, Brisswalter J, Smith D, Millet G, et al. Effect of two drafting modalities in cycling on running performance. Medicine and Science in Sports and Exercise. 2001;33(3):485-92.

93.Gianotti SM, Marshall SW, Hume PA, Bunt L. Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study. Journal of Science and Medicine in Sport. 2009;12(6):622-7.

94.TriNZ. Tri NZ names High Performance Squad Auckland2013. Available from: http://www.triathlon.org.nz/blog/id722/.

95.High Performance Sport New Zealand collection and use of athlete information brief, (2012).

96.O'Toole M, Douglas P, Hiller WD. Applied physiology of a triathlon. Sports Medicine. 1989;8(4):201-25.

97.Wilk BR, Fisher KL, Rangelli D. The incidence of musculoskeletal injuries in an amateur triathlete racing club. Journal of Orthopaedic an Sports Physical Therapy. 1995;22(3):108-12.

98.Taunton JE, Ryan MB, Clement DB, McKenzie DC, Lloyd-Smith DR, Zumbo BD. A retrospective case-control analysis of 2002 running injuries. British Journal of Sports Medicine. 2002;36(2):95-101.

99.Mellion MB. Common cycling injuries. Sports Medicine. 1991;11(1):52-70.

100.Holmes JC, Pruitt AL, Whalen NJ. Iliotibial band syndrome in cyclists. The American Journal of Sports Medicine. 1993;21(3):419-24.

101.Dias Lopes A, Carlos, Yeung SS, Oliveira. What are the main running-related musculoskeletal injuries? Sports Medicine. 2012;42(10):891-905.

102.Muraoka T, Muramatsu T, Fukunaga T, Kanehisa H. Geometric and elastic properties of in vivo human Achilles tendon in young adults. Cells Tissues Organs. 2004;178(4):197-203.

103.Müller R, Siebert T, Blickhan R. Muscle preactivation control: Simulation of ankle joint adjustments at touchdown during running on uneven ground. Journal of Applied Biomechanics. 2012;28(6):718-25.

104.Novacheck TF. The biomechanics of running. Gait and Posture. 1998;7(1):77-95.

105.Zhang SN, Bates BT, Dufek JS. Contributions of lower extremity joints to energy dissipation during landings. Medicine and Science in Sports and Exercise. 2000;32(4):812-9.

106.Dixon SJ, Collop AC, Batt ME. Surface effects on ground reaction forces and lower extremity kinematics in running. Medicine and Science in Sports and Exercise. 2000;32(11):1919-26.

107.Ferris DP, Louie M, Farley CT. Running in the real world: Adjusting leg stiffness for different surfaces. Proceedings of the Royal Society of London Series B: Biological Sciences. 1998;265(1400):989-94.

108.Müller R, Grimmer S, Blickhan R. Running on uneven ground: Leg adjustments by muscle pre-activation control. Human Movement Science. 2010;29(2):299-310.

109.Maganaris CN, Narici MV, Maffulli N. Biomechanics of the Achilles tendon. Disability and Rehabilitation. 2008;30(20-22):1542-7.

110.Hintermann B, Nigg BM, Sommer C. Foot movement and tendon excursion: An in vitro study. Foot and Ankle International. 1994;15(7):386-95.

111.Wakahara T, Kanehisa H, Kawakami Y, Fukunaga T. Fascicle behavior of medial gastrocnemius muscle in extended and flexed knee positions. Journal of Biomechanics. 2007;40(10):2291-8.

112.Lersch C, Grötsch A, Segesser B, Koebke J, Brüggemann G-P, Potthast W. Influence of calcaneus angle and muscle forces on strain distribution in the human Achilles tendon. Clinical Biomechanics. 2012;27(9):955-61.

113.Lyman J, Weinhold PS, Almekinders LC. Strain behavior of the distal Achilles tendon implications for insertional Achilles tendinopathy. The American Journal of Sports Medicine. 2004;32(2):457-61.

114.Wren TAL, Lindsey DP, Beaupré GS, Carter DR. Effects of creep and cyclic loading on the mechanical properties and failure of human Achilles tendons. Annals of Biomedical Engineering. 2003;31(6):710-7.

115.Alfredson H, Lorentzon R. Chronic Achilles tendinosis. Sports Medicine. 2000;29(2):135-46.

116.Wen DY. Risk factors for overuse injuries in runners. Current Sports Medicine Reports. 2007;6(5):307-13.

117.Higgins JP, Green S, Collaboration C. Cochrane handbook for systematic reviews of interventions. Chichester, UK: Wiley Online Library; 2008.

118.Maher CG, Sherrington C, Herbert RD, Moseley AM, Elkins M. Reliability of the PEDro scale for rating quality of randomized controlled trials. Physical Therapy. 2003;83(8):713-21.

119.Bizzini M, Childs JD, Piva SR, Delitto A. Systematic review of the quality of randomized controlled trials for patellofemoral pain syndrome. Journal of Orthopaedic and Sports Physical Therapy. 2003;33(1):4-20.

120.Chinn S. A simple method for converting an odds ratio to effect size for use in meta-analysis. Statistics in Medicine. 2000;19(22):3127-31.

121.Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Medicine and Science in Sports and Exercise. 2009;41(1):3-13.

122.Kader D, Saxena A, Movin T, Maffulli N. Achilles tendinopathy: Some aspects of basic science and clinical management. British Journal of Sports Medicine. 2002;36(4):239-49.

123.Gosling C, Forbes A, Donaldson A, Gabbe B. The perception of injury risk and safety in triathlon: An exploratory focus group study. Journal of Science and Medicine in Sport. 2011;14:e54-e5.

124.Gosling CM, Forbes AB, Gabbe BJ. Health professionals' perceptions of musculoskeletal injury and injury risk factors in Australian triathletes: A factor analysis. Physical Therapy in Sport. 2012;21(12):1-6.

125.Knobloch K, Uzung Y, Vogt PM. Acute and overuse injuries correlated to hours of training in master running athletes. Foot and Ankle International. 2008;29(7):671-6.

126.Di Caprio F, Buda R, Mosca M, Calabrò A, Giannini S. Foot and lower limb diseases in runners: Assessment of risk factors. Journal of Sports Science and Medicine. 2010;9(4):587-96.

127.Van Ginckel A, Thijs Y, Hesar NGZ, Mahieu N, De Clercq D, Roosen P, et al. Intrinsic gait-related risk factors for Achilles tendinopathy in novice runners: A prospective study. Gait and Posture. 2009;29(3):387-91.

128.Haglund-Akerlind Y, Eriksson E. Range of motion, muscle torque and training habits in runners with and without Achilles tendon problems. Knee Surgery, Sports Traumatology, Arthroscopy. 1993;1(3-4):195-9.

129.Reule CA, Alt WW, Lohrer H, Hochwald H. Spatial orientation of the subtalar joint axis is different in subjects with and without Achilles tendon disorders. British Journal of Sports Medicine. 2011;45(13):1029-34.

130.Ryan M, Grau S, Krauss I, Maiwald C, Taunton J, Horstmann T. Kinematic analysis of runners with Achilles mid-portion tendinopathy. Foot and Ankle International. 2009;30(12):1190-5.

131.Williams III DS, Zambardino JA, Banning VA. Transverse-plane mechanics at the knee and tibia in runners with and without a history of achilles tendonopathy. Journal of Orthopaedic Sports Physical Therapy. 2008;38(12):761-7.

132.Azevedo LB. Biomechanical variables associated with Achilles tendinopathy in runners. British Journal of Sports Medicine. 2009;43(4):288-92.

133.Baur H, Divert C, Hirschmüller A, Müller S, Belli A, Mayer F. Analysis of gait differences in healthy runners and runners with chronic Achilles tendon complaints. Isokinetics and Exercise Science. 2004;12(2):111-6.

134.Baur H, Muller S, Hirschmuller A, Cassel M, Weber J, Mayer F. Comparison in lower leg neuromuscular activity between runners with unilateral mid-portion Achilles tendinopathy and healthy individuals. Journal of Electromyography and Kinesiology. 2011;21(3):499-505.

135.Wyndow N, Cowan SM, Wrigley TV, Crossley KM. Triceps surae activation is altered in male runners with Achilles tendinopathy. Journal of Electromyography and Kinesiology. 2013;23(1):166-72.

136.McCrory JL, Martin DF, Lowery RB, Cannon DW, Curl WW, Read HM, et al. Etiologic factors associated with Achilles tendinitis in runners. Medicine and Science in Sports and Exercise. 1999;31(10):1374-81.

137.Maquirriain J. Leg stiffness changes in athletes with Achilles tendinopathy. International Journal of Sports Medicine. 2012;33(7):567-71.

138.Kaufman KR, Brodine SK, Shaffer RA, Johnson CW, Cullison TR. The effect of foot structure and range of motion on musculoskeletal overuse injuries. American Journal of Sports Medicine. 1999;27(5):585-93.

139.Mahieu NN, Witvrouw E, Stevens V, Van Tiggelen D, Roget P. Intrinsic risk factors for the development of Achilles tendon overuse injury. A prospective study. American Journal of Sports Medicine. 2006;34(2):226-35.

140.Longo UG, Rittweger J, Garau G, Radonic B, Gutwasser C, Gilliver SF, et al. No influence of age, gender, weight, height, and impact profile in achilles tendinopathy in masters track and field athletes. American Journal of Sports Medicine. 2009;37(7):1400-5.

141.Gaida JE, Alfredson H, Kiss ZS, Bass SL, Cook JL. Asymptomatic Achilles tendon pathology is associated with a central fat distribution in men and a peripheral fat distribution in women: A cross sectional study of 298 individuals. BMC Musculoskeletal Disorders. 2010;11(1):41.

142.Galloway MT, Jokl P, Dayton OW. Achilles tendon overuse injuries. Clinics in Sports Medicine. 1992;11(4):771-82.

143.Farley CT, Houdijk HHP, Van Strien C, Louie M. Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. Journal of Applied Physiology. 1998;85(3):1044-55.

144.Ferris DP, Farley CT. Interaction of leg stiffness and surface stiffness during human hopping. Journal of Applied Physiology. 1997;82(1):15-22.

145.Ferris DP, Liang K, Farley CT. Runners adjust leg stiffness for their first step on a new running surface. Journal of Biomechanics. 1999;32(8):787-94.

146.Kerdok AE, Biewener AA, McMahon TA, Weyand PG, Herr HM. Energetics and mechanics of human running on surfaces of different stiffnesses. Journal of Applied Physiology. 2002;92(2):469-78.

147.Hardin EE, Van den Bogert AJ, Hamill J. Kinematic adaptations during running: Effects of footwear, surface, and duration. Medicine and Science in Sports and Exercise. 2004;36(5):838-44.

148.Williams III DS, McClay IS, Hamill J. Arch structure and injury patterns in runners. Clinical Biomechanics. 2001;16(4):341-7.

149.Williams III DS, Davis IM, Scholz JP, Hamill J, Buchanan TS. High-arched runners exhibit increased leg stiffness compared to low-arched runners. Gait and Posture. 2004;19(3):263-9.

150.Öhberg L, Lorentzon R, Alfredson H. Eccentric training in patients with chronic Achilles tendinosis: Normalised tendon structure and decreased thickness at follow up. British Journal of Sports Medicine. 2004;38(1):8-11.

151.Fahlström M, Jonsson P, Lorentzon R, Alfredson H. Chronic Achilles tendon pain treated with eccentric calf-muscle training. Knee Surgery, Sports Traumatology, Arthroscopy. 2003;11(5):327-33.

152.Alfredson H, Pietilä T, Jonsson P, Lorentzon R. Heavy-load eccentric calf muscle training for the treatment of chronic Achilles tendinosis. American Journal of Sports Medicine. 1998;26(3):360-6.

153.Henriksen M, Aaboe J, Bliddal H, Langberg H. Biomechanical characteristics of the eccentric Achilles tendon exercise. Journal of Biomechanics. 2009;42(16):2702-7.

154.Arndt A, Brueggemann GP, Koebke J, Segesser B. Asymmetrical loading of the human triceps surae. I. Mediolateral force differences in the Achilles tendon. Foot and Ankle International. 1999;20(7):444-9.

155.Hamill J, van Emmerik RE, Heiderscheit BC, Li L. A dynamical systems approach to lower extremity running injuries. Clinical Biomechanics. 1999;14(5):297-308.

156.Arya S, Kulig K. Tendinopathy alters mechanical and material properties of the Achilles tendon. Journal of Applied Physiology. 2010;108(3):670-5.

157.Arya S. Mechanical properties of degenerated tendons and their influence on lower extremity biomechanics: University of South California; 2008.

158.Kubo K, Morimoto M, Komuro T, Tsunoda N, Kanehisa H, Fukunaga T. Influences of tendon stiffness, joint stiffness, and electromyographic activity on jump performances using single joint. European Journal of Applied Physiology. 2007;99(3):235-43.

159.McMahon TA, Cheng GC. The mechanics of running: How does stiffness couple with speed? Journal of Biomechanics. 1990;23(S1):65-78.

160.Davids K, Button C, Bennett S. Physical constraints on coordination: Dynamical systems theory. Dynamics of skill acquisition: A constraints-led approach. Champaign, IL: Human Kinetics; 2008. p. 29-53.

161.Chapter 2. Lower limb overuse injuries in New Zealand high performance triathletes: AUT University; 2014.

162.Ericson MO, Ekholm J, Svensson O, Nisell R. The forces of ankle joint structures during ergometer cycling. Foot and Ankle International. 1985;6(3):135-42.

163.Gregor R, Komi P, Järvinen M. Achilles tendon forces during cycling. International Journal of Sports Medicine. 1987;8(S1):S9-S14.

164.Ericson M. On the biomechanics of cycling. A study of joint and muscle load during exercise on the bicycle ergometer. Scandinavian Journal of Rehabilitation Medicine. 1986;16(S1):1-43.

165.Giddings VL, Beaupre GS, Whalen RT, Carter DR. Calcaneal loading during walking and running. Medicine and Science in Sports and Exercise. 2000;32(3):627-34.

166.Komi PV. Stretch-shortening cycle: A powerful model to study normal and fatigued muscle. Journal of Biomechanics. 2000;33(10):1197-206.

167.Lorimer AV, Hume PA. Achilles tendon injury risk factors associated with running. Sports Medicine. 2014;44(10):1459-72.

168.Sobhani S, Dekker R, Postema K, Dijkstra PU. Epidemiology of ankle and foot overuse injuries in sports: A systematic review. Scandinavian Journal of Medicine and Science in Sports. 2013;23(6):669-86.

169.Davids K, Glazier P, Araujo D, Bartlett R. Movement systems as dynamical systems: The functional role of variability and its implications for sports medicine. Sports Medicine. 2003;33(4):245-60.

170.Blickhan R. The spring-mass model for running and hopping. Journal of Biomechanics. 1989;22(11-12):1217-27.

171.Seyfarth A, Geyer H, Günther M, Blickhan R. A movement criterion for running. Journal of Biomechanics. 2002;35(5):649-55.

172.Duysens J, Van de Crommert HWAA. Neural control of locomotion Part 1: The central pattern generator from cats to humans. Gait and Posture. 1998;7(2):131-41.

173.Ijspeert AJ. Central pattern generators for locomotion control in animals and robots: A review. Neural Networks. 2008;21(4):642-53.

174.Dunlap WP, Cortina JM, Vaslow JB, Burke MJ. Meta-analysis of experiments with matched groups or repeated measures designs. Psychological Methods. 1996;1(2):170-7.

175.Girard O, Millet G, Slawinski J, Racinais S, Micallef J. Changes in running mechanics and spring-mass behaviour during a 5-km time trial. International Journal of Sports Medicine. 2013;34(9):832-40.

176.Rabita G, Couturier A, Lambertz D. Intrinsic ankle and hopping leg-spring stiffness in distance runners and aerobic gymnasts. International Journal of Sports Medicine. 2011;32(7):552-8.

177.Dutto DJ, Smith GA. Changes in spring-mass characteristics during treadmill running to exhaustion. Medicine and Science in Sports and Exercise. 2002;34(8):1324-31.

178.Girard O, Micallef J-P, Millet GP. Changes in spring-mass model characteristics during repeated running sprints. European Journal of Applied Physiology. 2011;111(1):125-34.

179.Moritz CT, Farley CT. Passive dynamics change leg mechanics for an unexpected surface during human hopping. Journal of Applied Physiology. 2004;97(4):1313-22.

180.Arampatzis A, Bruggemann GP, Metzler V. The effect of speed on leg stiffness and joint kinetics in human running. Journal of Biomechanics. 1999;32(12):1349-53.

181.Hobara H, Inoue K, Gomi K, Sakamoto M, Muraoka T, Iso S, et al. Continuous change in spring-mass characteristics during a 400m sprint. Journal of Science and Medicine in Sport. 2010;13(2):256-61.

182.Morin J-B, Jeannin T, Chevallier B, Belli A. Spring-mass model characteristics during sprint running: correlation with performance and fatigue-induced changes. International Journal of Sports Medicine. 2006;27(2):158-65.

183.Kuitunen S, Komi PV, Kyrolainen H. Knee and ankle joint stiffness in sprint running. Medicine and Science in Sports and Exercise. 2002;34(1):166-73.

184.Jacobs SJ, Berson BL. Injuries to runners: A study of entrants to a 10,000 meter race. The American Journal of Sports Medicine. 1986;14(2):151-5.

185.Hobara H, Kanosue K, Suzuki S. Changes in muscle activity with increase in leg stiffness during hopping. Neuroscience Letters 2007;418(1):55-9.

186.Morin JB, Samozino P, Zameziati K, Belli A. Effects of altered stride frequency and contact time on leg-spring behavior in human running. Journal of Biomechanics. 2007;40(15):3341-8.

187.Hobara H, Inoue K, Muraoka T, Omuro K, Sakamoto M, Kanosue K. Leg stiffness adjustment for a range of hopping frequencies in humans. Journal of Biomechanics. 2010;43(3):506-11.

188.Hoffrén M, Ishikawa M, Rantalainen T, Avela J, Komi PV. Age-related muscle activation profiles and joint stiffness regulation in repetitive hopping. Journal of Electromyography and Kinesiology. 2011;21(3):483-91.

189.Austin GP, Tiberio D, Garrett GE. Effect of frequency on human unipedal hopping. Perceptual and Motor Skills. 2002;95(3):733-40.

190.Farley CT, Gonzalez O. Leg stiffness and stride frequency in human running. Journal of Biomechanics. 1996;29(2):181-6.

191.Hunter JP, Marshall RN, McNair PJ. Interaction of step length and step rate during sprint running. Medicine and Science in Sports and Exercise. 2004;36(2):261-71.

192.Hobara H, Inoue K, Kanosue K. Effect of hopping frequency on bilateral differences in leg stiffness. Journal of Applied Biomechanics. 2013;29(1):55-60.

193.Hobara H, Inoue K, Omuro K, Muraoka T, Kanosue K. Determinant of leg stiffness during hopping is frequency-dependent. European Journal of Applied Physiology. 2011;111(9):2195-201.

194.Demirbüken İ, Yurdalan SU, Savelberg H, Meijer K. Gender specific strategies in demanding hopping conditions. Journal of Sports Science and Medicine. 2009;8(2):265-70.

195.Hobara H, Kato E, Kobayashi Y, Ogata T. Sex differences in relationship between passive ankle stiffness and leg stiffness during hopping. Journal of Biomechanics. 2012;45(16):2750-4.

196.Granata KP, Padua DA, Wilson SE. Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. Journal of Electromyography and Kinesiology. 2002;12(2):127-35.

197.Padua DA, Arnold BL, Perrin DH, Gansneder BM, Carcia CR, Granata KP. Fatigue, vertical leg stiffness, and stiffness control strategies in males and females. Journal of Athletic Training. 2006;41(3):294-304.

198.Oliver JL, Smith PM. Neural control of leg stiffness during hopping in boys and men. Journal of Electromyography and Kinesiology. 2010;20(5):973-9.

199.Divert C, Mornieux G, Freychat P, Baly L, Mayer F, Belli A. Barefoot-shod running differences: Shoe or mass effect? International Journal of Sports Medicine. 2008;29(6):512-8.

200.Bishop M, Fiolkowski P, Conrad B, Brunt D, Horodyski M. Athletic footwear, leg stiffness, and running kinematics. Journal of Athletic Training. 2006;41(4):387-92.

201.Logan S, Hunter I, Hopkins JT, Feland JB, Parcell AC. Ground reaction force differences between running shoes, racing flats, and distance spikes in runners. Journal of Sports Science and Medicine. 2010;9(1):147-53.

202.Kuitunen S, Ogiso K, Komi P. Leg and joint stiffness in human hopping. Scandinavian Journal of Medicine and Science in Sports. 2011;21(6):e159-e67.

203.Hobara H, Kimura K, Omuro K, Gomi K, Muraoka T, Sakamoto M, et al. Differences in lower extremity stiffness between endurance-trained athletes and untrained subjects. Journal of Science and Medicine in Sport. 2010;13(1):106-11.

204.Choukou M-A, Laffaye G, Heugas-De Panafieu A-M. Sprinter's motor signature does not change with fatigue. European Journal of Applied Physiology. 2012;112(4):1557-68.

205.Degache F, Guex K, Fourchet F, Morin JB, Millet GP, Tomazin K, et al. Changes in running mechanics and spring-mass behaviour induced by a 5-hour hilly running bout. Journal of Sports Sciences. 2013;31(3):299-304.

206.Hunter I, Smith GA. Preferred and optimal stride frequency, stiffness and economy: Changes with fatigue during a 1-h high-intensity run. European Journal of Applied Physiology. 2007;100(6):653-61.

207.Millet GY, Divert C, Banizette M, Morin J-B. Changes in running pattern due to fatigue and cognitive load in orienteering. Journal of Sports Sciences. 2010;28(2):153-60.

208.Morin J, Tomazin K, Edouard P, Millet G. Changes in running mechanics and spring–mass behavior induced by a mountain ultra-marathon race. Journal of Biomechanics. 2011;44(6):1104-7.

209.Morin J-B, Samozino P, Millet GY. Changes in running kinematics, kinetics, and spring-mass behavior over a 24-h run. Medicine and Science in Sports and Exercise. 2011;43(5):829-36.

210.Morin J-B, Tomazin K, Samozino P, Edouard P, Millet GY. High-intensity sprint fatigue does not alter constant-submaximal velocity running mechanics and spring-mass behavior. European Journal of Applied Physiology. 2012;112(4):1419-28.

211.Le Meur Y, Thierry B, Rabita G, Dorel S, Honnorat G, Brisswalter J, et al. Spring-mass behaviour during the run of an international triathlon competition. International Journal of Sports Medicine. 2013;34(8):1-8.

212.Rabita G, Couturier A, Dorel S, Hausswirth C, Le Meur Y. Changes in spring-mass behavior and muscle activity during an exhaustive run at VO2max. Journal of Biomechanics. 2013;46(12):2011-7.

213.Slawinski J, Heubert R, Quievre J, Billat V, Hannon C. Changes in spring-mass model parameters and energy cost during track running to exhaustion. Journal of Strength and Conditioning Research. 2008;22(3):930-6.

214.Le Meur Y, Dorel S, Rabita G, Bernard T, Brisswalter J, Hausswirth C. Spring–mass behavior and electromyographic activity evolution during a cycle-run test to exhaustion in triathletes. Journal of Electromyography and Kinesiology. 2012;22(6):835-44.

215.Lipfert SW, Günther M, Renjewski D, Grimmer S, Seyfarth A. A model-experiment comparison of system dynamics for human walking and running. Journal of Theoretical Biology. 2012;292:11-7.

216.Padua DA, Carcia CR, Arnold BL, Granata KP. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. Journal of Motor Behaviour. 2005;37(2):111-25.

217.Viale F, Dalleau G, Freychat P, Lacour J-R, Belli A. Leg stiffness and foot orientations during running. Foot and Ankle International. 1998;19(11):761-5.

218.Marti B, Vader JP, Minder CE, Abelin T. On the epidemiology of running injuries The 1984 Bern Grand-Prix study. The American Journal of Sports Medicine. 1988;16(3):285-94.

219.Hoyt DF, Wickler SJ, Cogger EA. Time of contact and step length: The effect of limb length, running speed, load carrying and incline. Journal of Experimental Biology. 2000;203(2):221-7.

220.Onambele GL, Narici MV, Maganaris CN. Calf muscle-tendon properties and postural balance in old age. Journal of Applied Physiology. 2006;100(6):2048-56.

221.Hamill J, Russell EM, Gruber AH, Miller R. Impact characteristics in shod and barefoot running. Footwear Science. 2011;3(1):33-40.

222.Perry SD, Lafortune MA. Influences of inversion/eversion of the foot upon impact loading during locomotion. Clinical Biomechanics. 1995;10(5):253-7.

223.Nigg BM. The role of impact forces and foot pronation: A new paradigm. Clinical Journal of Sport Medicine. 2001;11(1):2-9.

224.Millet GP, Vleck VE. Physiological and biomechanical adaptations to the cycle to run transition in Olympic triathlon: Review and practical recommendations for training. British Journal of Sports Medicine. 2000;34(5):384-90.

225.Bonacci J, Green D, Saunders PU, Blanch P, Franettovich M, Chapman AR, et al. Change in running kinematics after cycling are related to alterations in running economy in triathletes. Journal of Science and Medicine in Sport. 2010;13(4):460-4.

226.Millet GP, Millet GY, Hofmann MD, Candau RB. Alterations in running economy and mechanics after maximal cycling in triathletes: Influence of performance level. International Journal of Sports Medicine. 2000;21(2):127-32.

227.Bentley DJ. The physiological responses to running after cycling in elite junior and senior triathletes. International Journal of Sports Medicine. 2004;25(3):191-7.

228.Rendos NK, Harrison BC, Dicharry JM, Sauer LD, Hart JM. Sagittal plane kinematics during the transition run in triathletes. Journal of Science and Medicine in Sport. 2013;16(3):259-65.

229.Chapman AR, Hodges PW, Briggs AM, Stapley PJ, Vicenzino B. Neuromuscular control and exercise-related leg pain in triathletes. Medicine and Science in Sports and Exercise. 2010;42(2):233-43.

230.Chapman AR, Vicenzino B, Blanch P, Dowlan S, Hodges PW. Does cycling effect motor coordination of the leg during running in elite triathletes? Journal of Science and Medicine in Sport. 2008;11(4):371-80.

231.Heiden T, Burnett A. Triathlon: The effect of cycling on muscle activation in the running leg of an Olympic distance triathlon. Sports Biomechanics. 2003;2(1):35-49.

232.Lepers R, Bigard AX, Diard J-P, Gouteyron J-F, Guezennec CY. Posture control after prolonged exercise. European Journal of Applied Physiology and Occupational Physiology. 1997;76(1):55-61.

233.Sainburg RL, Poizner H, Ghez C. Loss of proprioception produces deficits in interjoint coordination. Journal of Neurophysiology. 1993;70(5):2136-47.

234.McCole SD, Calney K, Conte JC, Anderson R, Hagberg JM. Energy expenditure during bicycling. Journal of Applied Physiology. 1990;68(2):748-53.

235.Chelly SM, Denis C. Leg power and hopping stiffness: Relationship with sprint running performance. Medicine and Science in Sports and Exercise. 2001;33(2):326-33.

236.Brughelli M, Cronin J. A review of research on the mechanical stiffness in running and jumping: Methodology and implications. Scandinavian Journal of Medicine and Science in Sports. 2008;18(4):417-26.

237.Fletcher JR, Esau SP, MacIntosh BR. Changes in tendon stiffness and running economy in highly trained distance runners. European Journal of Applied Physiology. 2010;110(5):1037-46.

238.Butler RJ, Davis IS, Hamill J. Interaction of arch type and footwear on running mechanics. American Journal of Sports Medicine. 2006;34(12):1998-2005.

239.Coleman DR, Cannavan D, Horne S, Blazevich AJ. Leg stiffness in human running: Comparison of estimates derived from previously published models to direct kinematic-kinetic measures. Journal of Biomechanics. 2012;45(11):1987-91.

240.Farley CT, Morgenroth DC. Leg stiffness primarily depends on ankle stiffness during human hopping. Journal of Biomechanics. 1999;32(3):267-73.

241.Farley CT, Blickhan R, Saito J, Taylor CR. Hopping frequency in humans: A test of how springs set stride frequency in bouncing gaits. Journal of Applied Physiology. 1991;71(6):2127-32.

242.Joseph CW, Bradshaw EJ, Kemp J, Clark RA. The interday reliability of ankle, knee, leg, and vertical musculoskeletal stiffness during hopping and overground running. Journal of Applied Biomechanics. 2013;29(4):386-94.

243.Morin JB, Dalleau G, Kyrolainen H, Jeannin T, Belli A. A simple method for measuring stiffness during running. Journal of Applied Biomechanics. 2005;21(2):167-80.

244.Günther M, Blickhan R. Joint stiffness of the ankle and the knee in running. Journal of Biomechanics. 2002;35(11):1459-74.

245.Giandolini M, Arnal P, Millet G, Peyrot N, Samozino P, Dubois B, et al. Impact reduction during running: Efficiency of simple acute interventions in recreational runners. European Journal of Applied Physiology. 2013;113(3):599-609.

246.Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation on joint mechanics during running. Medicine and Science in Sports and Exercise. 2011;43(2):296-302.

247.Grimmer S, Ernst M, Günther M, Blickhan R. Running on uneven ground: Leg adjustment to vertical steps and self-stability. Journal of Experimental Biology. 2008;211(18):2989-3000.

248.Greene PR, McMahon TA. Reflex stiffness of man's anti-gravity muscles during kneebends while carrying extra weights. Journal of Biomechanics. 1979;12(12):881-91.

249.Kyröläinen H, Komi PV, Belli A. Changes in muscle activity patterns and kinetics with increasing running speed. Journal of Strength and Conditioning Research. 1999;13(4):400-6.

250.Dietz V, Schmidtbleicher D, Noth J. Neuronal mechanisms of human locomotion. Journal of Neurophysiology. 1979;42(5):1212-22.

251.Ruan M. Maximize muscle mechanical output during the stretch-shortening cycle - The contribution of preactivation and stretch load: Louisiana State University; 2007.

252.Hobara H, Muraoka T, Omuro K, Gomi K, Sakamoto M, Inoue K, et al. Knee stiffness is a major determinant of leg stiffness during maximal hopping. Journal of Biomechanics. 2009;42(11):1768-71.

253.Lloyd RS, Oliver JL, Hughes MG, Williams CA. Reliability and validity of field-based measures of leg stiffness and reactive strength index in youths. Journal of Sports Sciences. 2009;27(14):1565-73.

254.McLachlan KA, Murphy AJ, Watsford ML, Rees S. The interday reliability of leg and ankle musculotendinous stiffness measures. Journal of Applied Biomechanics. 2006;22(4):296-304.

255.Blum Y, Lipfert SW, Seyfarth A. Effective leg stiffness in running. Journal of Biomechanics. 2009;42(14):2400-5.

256.Farley CT, Glasheen J, McMahon TA. Running springs: Speed and animal size. Journal of Experimental Biology. 1993;185(1):71-86.

257.Strocchi R, De Pasquale V, Guizzardi S, Govoni P, Facchini A, Raspanti M, et al. Human Achilles tendon: Morphological and morphometric variations as a function of age. Foot and Ankle International. 1991;12(2):100-4.

258.Silder A, Heiderscheit B, Thelen DG. Active and passive contributions to joint kinetics during walking in older adults. Journal of Biomechanics. 2008;41(7):1520-7.

259.Stewart A, Marfell-Jones M, Olds T, de Ridder H. International standards for anthropometric assessment. Lower Hutt, New Zealand: International Society for the Advancement of Kinanthropometry; 2011.

260.Besier TF, Sturnieks DL, Alderson JA, Lloyd DG. Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. Journal of Biomechanics. 2003;36(8):1159-68.

261.Tulchin K, Orendurff M, Karol L. A comparison of multi-segment foot kinematics during level overground and treadmill walking. Gait and posture. 2010;31(1):104-8.

262.Ferber R, McClay Davis I, Williams III DS. Gender differences in lower extremity mechanics during running. Clinical Biomechanics. 2003;18(4):350-7.

263.Piazza SJ, Okita N, Cavanagh PR. Accuracy of the functional method of hip joint center location: Effects of limited motion and varied implementation. Journal of Biomechanics. 2001;34(7):967-73.

264.Hopkins WG. Measures of reliability in sports medicine and science. Sports Medicine. 2000;30(1):1-15.

265.Bradshaw E, Hume P, Calton M, Aisbett B. Reliability and variability of day-to-day vault training measures in artistic gymnastics. Sports Biomechanics. 2010;9(2):79-97.

266.Rummel J, Iida F, Smith JA, Seyfarth A, editors. Enlarging regions of stable running with segmented legs. IEEE International Conference on Robotics and Automation, 2008 2008; Pasadena, CA: IEEE.

267.Brughelli M, Cronin J. Influence of running velocity on vertical, leg and joint stiffness. Sports Medicine. 2008;38(8):647-57.

268.Riley PO, Dicharry J, Franz J, Croce UD, Wilder RP, Kerrigan DC. A kinematics and kinetic comparison of overground and treadmill running. Medicine and Science in Sports and Exercise. 2008;40(6):1093-100.

269.Nigg BM, De Boer RW, Fisher V. A kinematic comparison of overground and treadmill running. Medicine and Science in Sports and Exercise. 1995;27(1):98-105.

270.Seyfarth A, Geyer H, Herr H. Swing-leg retraction: A simple control model for stable running. Journal of Experimental Biology. 2003;206(15):2547-55.

271.Challis JH. The variability in running gait caused by force plate targeting. Journal of Applied Biomechanics. 2001;17(1):77-83.

272.Hopkins WG. Estimating sample size for magnitude-based inferences. Sportscience. 2006;10:63-70.

273.Laughton CA, Davis IMC, Hamill J. Effect of strike pattern and orthotic intervention on tibial shock during running. Journal of Applied Biomechanics. 2003;19(2):153-68.

274.Winter DA. Overall principle of lower limb support during stance phase of gait. Journal of Biomechanics. 1980;13(11):923-7.

275.Lafortune MA, Hennig EM, Lake MJ. Dominant role of interface over knee angle for cushioning impact loading and regulating initial leg stiffness. Journal of Biomechanics. 1996;29(12):1523-9.

276.Mochon S, McMahon TA. Ballistic walking. Journal of Biomechanics. 1980;13(1):49-57.

277.Cavagna GA, Kaneko M. Mechanical work and efficiency in level walking and running. Journal of Physiology. 1977;268(2):467-81.

278.Mero A, Komi PV. EMG, force, and power analysis of sprint-specific strength exercises. Journal of Applied Biomechanics. 1994;10(1):1-13.

279.Chapter 4. Stiffness as a risk factor for Achilles tendon injury in triathletes and other running athletes: Systematic review. Auckland, New Zealand: Auckland University of Technology; 2014.

280.Chapter 5. Comparison of methods for quantifying stiffness and their reliability in triathletes. Auckland, New Zealand: Auckland University of Technology; 2014.

281.Chapman AR, Vicenzino B, Blanch P, Hodges PW. Is running less skilled in triathletes than runners matched for running training history? Medicine and Science in Sports and Exercise. 2008;40(3):557-65.

282.Chumanov ES, Wille CM, Michalski MP, Heiderscheit BC. Changes in muscle activation patterns when running step rate is increased. Gait and Posture. 2012;36(2):231-5.

283.Schubert AG, Kempf J, Heiderscheit BC. Influence of stride frequency and length on running mechanics: A systematic review. Sports Health. 2013;6(3):210-7.

284.Thompson M, Gutmann A, Seegmiller J, McGowan C. The effect of stride length on the dynamics of barefoot and shod running. Journal of Biomechanics. 2014;47(11):2745-50.

285.Jacobs R, Bobbert MF, van Ingen Schenau G. Function of mono- and biarticular muscles in running. Medicine and Science in Sports and Exercise. 1993;25(10):1163-73.

286.Meeuwisse WH. Assessing causation in sport injury: A multifactorial model. Clinical Journal of Sport Medicine. 1994;4(3):166-70.

287.Bernstein NA. The coordination and regulation of movement: London: Pergamon Press (Originally Russian); 1967.

288.Vereijken B, Emmerik REAv, Whiting HTA, Newell KM. Free(z)ing degrees of freedom in skill acquisition. Journal of Motor Behavior. 1992;24(1):133-42.

289.Berthouze L, Lungarella M. Motor skill acquisition under environmental perturbations: On the necessity of alternate freezing and freeing of degrees of freedom. Adaptive Behavior. 2004;12(1):47-64.

290.Kyröläinen H, Avela J, Komi PV. Changes in muscle activity with increasing running speed. Journal of Sports Sciences. 2005;23(10):1101-9.

291.Kyröläinen H, Finni T, Avela J, Komi PV. Neuromuscular behaviour of the triceps surae muscle-tendon complex during running and jumping. International Journal of Sports Medicine. 2003;24(3):153-5.

292.Chapter 6. Lower limb stiffness is affected by running pace in triathletes: AUT University; 2014.

293.Krivickas LS. Anatomical factors associated with overuse sports injuries. Sports Medicine. 1997;24(2):132-46.

294.Hausdorff JM, Zemany L, Peng C-K, Goldberger AL. Maturation of gait dynamics: Stride-to-stride variability and its temporal organization in children. Journal of Applied Physiology. 1999;86(3):1040-7.

295.Jordan K, Newell KM. The structure of variability in human walking and running is speed-dependent. Exercise and Sport Sciences Reviews. 2008;36(4):200-4.

296.Qu X, Yeo JC. Effects of load carriage and fatigue on gait characteristics. Journal of Biomechanics. 2011;44(7):1259-63.

297.Trezise J, Bartlett R, Bussey M. Coordination variability changes with fatigue in sprinters. International Journal of Sports Science and Coaching. 2011;6(3):357-64.

298.Danion F, Varraine E, Bonnard M, Pailhous J. Stride variability in human gait: he effect of stride frequency and stride length. Gait and Posture. 2003;18(1):69-77.

299.Belli A, Kyröläinen H, Komi PV. Moment and power of lower limb joints in running. International Journal of Sports Medicine. 2002;23(2):136-41.

300.Dengel DR, Flynn MG, Costill DL, Kirwan JP. Determinants of success during triathlon competition. Research quarterly for exercise and sport. 1989;60(3):234-8.

301.Sleivert GG, Rowlands DS. Physical and physiological factors associated with success in the triathlon. Sports Medicine. 1996;22(1):8-18.

302.Garrett WE, Kirkendall DT. Exercise and Sport Science: Lippincott Williams & Wilkins; 2000.

303.Hue O, Le Gallais D, Chollet D, Boussana A, Préfaut C. The influence of prior cycling on biomechanical and cardiorespiratory response profiles during running in triathletes. European Journal of Applied Physiology and Occupational Physiology. 1997;77(1-2):98-105.

304.Guezennec CY, Vallier JM, Bigard AX, Durey A. Increase in energy cost of running at the end of a triathlon. European Journal of Applied Physiology and Occupational Physiology. 1996;73(5):440-5.

305.Tew G. The effect of cycling cadence on subsequent 10km running performance in well-trained triathletes. Journal of Sports Science and Medicine. 2005;4(3):342-53.

306.Etxebarria N, Hunt J, Ingham S, Ferguson R. Physiological assessment of isolated running does not directly replicate running capacity after triathlon-specific cycling. Journal of Sports Sciences. 2013;32(3):229-38.

307.Bonacci J, Saunders PU, Alexander M, Blanch P, Vicenzino B. Neuromuscular control and running economy is preserved in elite international triathletes after cycling. Sports Biomechanics. 2011;10(1):59-71.

308.Bernard T, Vercruyssen F, Grego F, Hausswirth C, Lepers R, Vallier JM, et al. Effect of cycling cadence on subsequent 3 km running performance in well trained triathletes. British Journal of Sports Medicine. 2003;37(2):154-9.

309.Chapman AR, Vicenzino B, Hodges PW, Blanch P, Hahn AG, Milner TE. A protocol for measuring the direct effect of cycling on neuromuscular control of running in triathletes. Journal of Sports Sciences. 2009;27(7):767-82.

310.Quigley EJ, Richards JG. The effects of cycling on running mechanics. Journal of Applied Biomechanics. 1996;12(4):470-9.

311.Gottschall JS, Palmer BM. Acute effects of cycling on running step length and step frequency. Journal of Strength and Conditioning Research. 2000;14(1):97-101.

312.Garside I, Doran DA. Effects of bicycle frame ergonomics on triathlon 10-km running performance. Journal of Sports Sciences. 2000;18(10):825-33.

313.Landers GJ, Blanksby BA, Ackland TR. Cadence, stride rate and stride length during triathlon competition. International Journal of Exercise Science. 2011;4(1):40-8.

314.Mon J, Maañón R, Viana O, Sánchez JA, Martín R, Fernández M, editors. Influence of cycling intensity on running kinematics and electromiography in well trained triathletes. 31st Congress of American Society of Biomechanics; 2007; Palo Alto, CA.

315.Bonacci J, Blanch P, Chapman AR, Vicenzino B. Altered movement patterns but not muscle recruitment in moderately trained triathletes during running after cycling. Journal of Sports Sciences. 2010;28(13):1477-87.

316.Kvist M. Achilles tendon injuries in athletes. Sports Medicine. 1994;18(3):173-201.

317.Heckman DS, Gluck GS, Parekh SG. Tendon disorders of the foot and ankle. Part 2: Achilles tendon disorders. American Journal of Sports Medicine. 2009;37(6):1223-34.

318.Chapter 8. Influence of prior cycling on lower limb stiffness in triathletes. Auckland, New Zealand: Auckland University of Technology; 2014.

319.Horgan CO, Murphy JG. On the normal stresses in simple shearing of fiber-reinforced nonlinearly elastic materials. Journal of Elasticity. 2011;104(1-2):343-55.

320.Bijker K, De Groot G, Hollander A. Differences in leg muscle activity during running and cycling in humans. European Journal of Applied Physiology. 2002;87(6):556-61.

321.Ericson MO, Bratt A, Nisell R, Arborelius UP, Ekholm J. Power output and work in different muscle groups during ergometer cycling. European Journal of Applied Physiology and Occupational Physiology. 1986;55(3):229-35.

322.Cannon DT, Kolkhorst FW, Cipriani DJ. Effect of pedaling technique on muscle activity and cycling efficiency. European Journal of Applied Physiology. 2007;99(6):659-64.

323.Sanderson DJ, Amoroso AT. The influence of seat height on the mechanical function of the triceps surae muscles during steady-rate cycling. Journal of Electromyography and Kinesiology. 2009;19(6):e465-e71.

324.So RC, Ng JK-F, Ng GY. Muscle recruitment pattern in cycling: A review. Physical Therapy in Sport. 2005;6(2):89-96.

325.Chapter 7. Reliability and variability of lower limb stiffness with changes in running pace for triathletes: AUT University; 2014.

326.Nielsen RO, Nohr EA, Rasmussen S, Sørensen H. Classifying running-related injuries based upon etiology, with emphasis on volume and pace. International Journal of Sports Physical Therapy. 2013;8(2):172.

327.Todorov E, Jordan MI. Optimal feedback control as a theory of motor coordination. Nature Neuroscience. 2002;5(11):1226-35.

328.Bartlett R, Wheat J, Robins M. Is movement variability important for sports biomechanists? Sports Biomechanics. 2007;6(2):224-43.

329.James CR, Dufek JS, Bates BT. Effects of injury proneness and task difficulty on joint kinetic variability. Medicine and Science in Sports and Exercise. 2000;32(11):1833-44.

330.Hamill J, Haddad JM, Van Emmerik RE, editors. Overuse injuries in running: Do complex analyses help our understanding? 24 International Symposium on Biomechanics in Sports 2006; Salzburg, Austria.

331.Burns J, Keenan A-M, Redmond A. Foot type and overuse injury in triathletes. Journal of the American Podiatric Medical Association. 2005;95(3):235-41.

332.Gosling CM, Forbes AB, McGivern J, Gabbe BJ. A profile of injuries in athletes seeking treatment during a triathlon race series. American Journal of Sports Medicine. 2010;38(5):1007-14.

333.Watsford ML, Murphy AJ, McLachlan KA, Bryant AL, Cameron ML, Crossley KM, et al. A prospective study of the relationship between lower body stiffness and hamstring injury in professional Australian rules footballers. American Journal of Sports Medicine. 2010;38(10):2058-64.

334.Hein T, Janssen P, Wagner-Fritz U, Haupt G, Grau S. Prospective analysis of intrinsic and extrinsic risk factors on the development of Achilles tendon pain in runners. Scandinavian Journal of Medicine and Science in Sports. 2014;24(3):e201-e12.

335.Dalleau G, Belli A, Viale F, Lacour J, Bourdin M. A simple method for field measurements of leg stiffness in hopping. International Journal of Sports Medicine. 2004;25(3):170-6.

336.Blickhan R, Full RJ. Similarity in multilegged locomotion: Bouncing like a monopode. J Comp Physiol A. 1993 1993/11/01;173(5):509-17.

337.Stergiou N, Decker LM. Human movement variability, nonlinear dynamics, and pathology: Is there a connection? Human Movement Science. 2011;30(5):869-88.

338.Jordan K, Challis JH, Newell KM. Speed influences on the scaling behavior of gait cycle fluctuations during treadmill running. Human Movement Science. 2007;26(1):87-102.

339.Silder A, Gleason K, Thelen DG. Influence of bicycle seat tube angle and hand position on lower extremity kinematics and neuromuscular control: Implications for triathlon running performance. Journal of Applied Biomechanics. 2011;27(4):297-305.

340.Arampatzis A, Karamanidis K, Stafilidis S, Morey-Klapsing G, DeMonte G, Brüggemann G-P. Effect of different ankle- and knee-joint positions on gastrocnemius medialis fascicle length and EMG activity during isometric plantar flexion. Journal of Biomechanics. 2006;39(10):1891-902.

APPENDIX 1

AUT ETHICS COMMITTEE APPROVAL – 3RD JUNE 2011

MEMORANDUM

Auckland University of Technology Ethics Committee (AUTEC)

To:Patria Hume

From:Dr Rosemary Godbold and Madeline Banda Executive Secretary, AUTEC

Date: 3 June 2011

Subject:Ethics Application Number 11/94 Reliability of stiffness measures for running.

Dear Patria

Thank you for providing written evidence as requested. We are pleased to advise that it satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC) at their meeting on 9 May 2011 and that on 30 May 2011, we approved your ethics application. This delegated approval is made in accordance with section 5.3.2.3 of AUTEC's *Applying for Ethics Approval: Guidelines and Procedures* and is subject to endorsement at AUTEC's meeting on 27 June 2011.

Your ethics application is approved for a period of three years until 30 May 2014.

We advise that as part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/research/research-ethics/ethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 30 May 2014;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/research/research-ethics/ethics. This report is to be submitted either

when the approval expires on 30 May 2014 or on completion of the project, whichever comes sooner;

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are reminded that, as applicant, you are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

Please note that AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to make the arrangements necessary to obtain this. Also, if your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply within that jurisdiction.

When communicating with us about this application, we ask that you use the application number and study title to enable us to provide you with prompt service. Should you have any further enquiries regarding this matter, you are welcome to contact Charles Grinter, Ethics Coordinator, by email at ethics@aut.ac.nz or by telephone on 921 9999 at extension 8860.

On behalf of AUTEC and ourselves, we wish you success with your research and look forward to reading about it in your reports.

Yours sincerely

Dr Rosemary Godbold and Madeline Banda

Executive Secretary

Auckland University of Technology Ethics Committee

Cc:Anna Lorimer fjd7588@aut.ac.nz

APPENDIX 2

AUT ETHICS COMMITTEE APPROVAL – 12TH DECEMBER 2011

MEMORANDUM

Auckland University of Technology Ethics Committee (AUTEC)

To: Patria Hume

From:**Dr Rosemary Godbold** Executive Secretary, AUTEC

Date:12 December 2011

Subject:Ethics Application Number 11/276 Identifying risk factors for Achilles tendon injuries in triathletes.

Dear Patria

Thank you for providing written evidence as requested. I am pleased to advise that it satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC) at their meeting on 10 October 2011 and I have approved your ethics application and a minor amendment of allowing the additional data collection method. This delegated approval is made in accordance with section 5.3.2.3 of AUTEC's *Applying for Ethics Approval: Guidelines and Procedures* and is subject to endorsement at AUTEC's meeting on 23 January 2012.

Your ethics application is approved for a period of three years until 12 December 2014.

I advise that as part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/research/research-ethics/ethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 12 December 2014;

- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/research/research-ethics/ethics. This report is to be submitted either when the approval expires on 12 December 2014 or on completion of the project, whichever comes sooner;

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are reminded that, as applicant, you are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

Please note that AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to make the arrangements necessary to obtain this.

When communicating with us about this application, we ask that you use the application number and study title to enable us to provide you with prompt service. Should you have any further enquiries regarding this matter, you are welcome to contact me by email at ethics@aut.ac.nz or by telephone on 921 9999 at extension 6902.

On behalf of AUTEC and myself, I wish you success with your research and look forward to reading about it in your reports.

Yours sincerely

Dr Rosemary Godbold

Executive Secretary

Auckland University of Technology Ethics Committee

Cc:Anna Lorimer alorimer@aut.ac.nz

APPENDIX 3

TABLE OF STUDY CHARACTERISTICS AND QUALITY SCORES – CHAPTER 4

Reference	QS	Study design	n, gender	Activity level	Movement	Stiffness	Normalisation	Factors
Arampatzis et al. (180)	4	Within subject repeated measure crossover	13	Experienced runners	Run	Kinematic	None	Velocity
Austin et al. (189)	5	Within subject repeated measure randomised crossover	10 M	-	Unipedal hop	Dynamic	None	Hop frequency
Bishop et al. (200)	5	Within subject repeated measure	9 (3F, 6M)	Physically active	Hop (2.2 Hz)	Dynamic	None	Footwear (BF, shoe)
Choukou et al. (204)	7	Within subject repeated measure, time series	8 M	Sprinters (regional)	Sprint	Time	None	Fatigue (4 x 100 m sprint)
Degache et al. (205)	5	Within subject repeated measure pre/post	8 M	Long distance trail runners	Treadmill run (2.8, 3.3, 3.9 m/s)	Time + Force	None	Fatigue (5 hr hilly run)
Demirbüken et al. (194)	6	Between subject repeated measure	22 (11F, 11M)	-	Bipedal hop (2.2 Hz)	Dynamic	None	Gender
Divert et al. (199)	8	Within subject repeated measure balanced crossover	12 M	Long distance runners	Treadmill run (3.6 m/s)	Dynamic	None	Footwear
Dutto & Smith (177)	7	Within subject repeated measure time series	15 (4F, 11M)	Long distance runners	Treadmill run (80% VO_{2peak} - $\bar{x}$=4.03 m/s)	Dynamic	None	Fatigue (to exhaustion), F_{zmax}, stride rate
Farley & Gonzalez (190)	4	Within subject repeated measures crossover	4 M	Experienced treadmill runners	Treadmill run (2.5 m/s)	Dynamic	None	Stride rate (pref. $\bar{x}$=1.33 Hz)
Farley et al. (143)	4	Within subject repeated measures crossover	7 (4F, 3M)	-	Bipedal hop (2.2 Hz)	Dynamic, Moment	None	Surface stiffness
Ferris & Farley (144)	4	Within subject repeated measure crossover	5 (3F, 2M)	-	Bipedal hop (2.0 Hz)	Dynamic	None	Surface stiffness

Reference	QS	Study design	n, gender	Activity level	Movement	Stiffness	Normalisation	Factors
Ferris et al. (107)	4	Within subject repeated measure crossover	5	-	Run (5.0 m/s)	Dynamic	None	Surface stiffness
Ferris et al. (145)	4	Within subject repeated measure crossover	6 F	-	Run (3.0 m/s)	Dynamic	None	Surface stiffness
Girard et al. (178)	6	Within subject repeated measure time series	16 M	Recreational team or racket sports athletes	Sprint (max effort)	Dynamic (last 5 m)	None	Fatigue (12 x 40 m sprints), Performance variables, F_{zmax}
Girard et al. (175)	7	Within subject repeated measure time series	12 M	Triathletes (national or regional)	Run (pref.)	Dynamic	None	Fatigue (5 km time trial), F_{ymax}, F_{ymin}, F_{zmax}, Performance variables
Granata et al. (196)	6	Between subject age matched	30 (15F, 15M)	-	Bipedal hop (pref. – x̄=2.3(F)- 2.4(M) Hz)	Dynamic	None	Gender
Hobara et al. (185)	6	Within subject repeated measure randomised crossover	7 M	-	Bipedal hop (pref. – x̄=2.1 Hz)	Time	None	Contact time, muscle activity
Hobara et al. (181)	6	Within subject repeated measure time series	8 M	Trained sprinters	Sprint (max effort)	Time	None	Fatigue (400 m sprint), Performance variables
Hobara et al. (187)	6	Within subject repeated measure randomised crossover	10 M	-	Bipedal hop	Dynamic, Moment	None	Hopping frequency
Hobara et al. (193)	8	Within subject repeated measure randomised crossover	14 M	Track and field athletes	Bipedal hop	Dynamic, Moment	Body mass	Hopping frequency
Hobara et al. (195)	8	Between subject repeated measure	20 (10F, 10M)	Sedentary, mildly active	Bipedal hop (2.0, 2.5 Hz)	Dynamic	Body mass	Gender, Passive stiffness
Hoffrén et al. (188)	5	Between subject repeated measure	33 [9 young (x̄=25.4 y), 24 elderly (x̄=71.7 y)]	Physically active	Bipedal hop (submax)	Moment	None	Age, Muscle activity
Hunter & Smith (206)	8	Within subject repeated measure randomised crossover	16 (5F, 11M)	Recreational runners	Run (78% VO_{2max} – 3.0 – 4.6 m/s)	Dynamic	None	Fatigue, stride rate

Reference	QS	Study design	n, gender	Activity level	Movement	Stiffness	Normalisation	Factors
Kerdok et al. (146)	5	Within subject repeated measure mirrored crossover	8 M	-	Run (3.7 m/s)	Kinematic + Force	None	Surface stiffness
Kuitunen et al. (183)	6	Within subject repeated measure randomised crossover	10 M	Sprinters	Sprint	Dynamic, Moment	None	Velocity, t_c
Kuitunen et al. (202)	6	Within subject repeated measure randomised crossover	8 M	Physically active	Bipedal hop	Dynamic + COM, Moment	None	Intensity/BW load, Muscle activity
Le Meur et al. (214)	7	Within subject repeated measure pre/post	10 M	Well-trained triathletes	Run (LT – $\bar{x}$=4.4 m/s)	Time	None	Transition (5 min control run, 30 min cycle 80% VO_{2max}, run exhaustion
Le Meur et al. (211)	7	Within subject repeated measure time series	73 (36F, 43 M)	Elite triathletes	Run (race)	Time	None	Fatigue (10 km run)
Lipfert et al. (215)	4	Within subject repeated measure crossover	7 (1F, 6M)	-	Treadmill run	Dynamic	None	Velocity
Logan et al. (201)	7	Between and within subject repeated measure randomised crossover	20 (10F, 10M)	National distance track or cross country runners	Run	Optimised (Hunter 2003)	Body mass	Footwear (shoes, flats, spikes)
Millet et al. (207)	7	Within subject repeated measure pre/post	19 (4F, 15M)	Orienteers	Run (70% VO_{2max} – $\bar{x}$= 3.7-4.1 m/s)	Dynamic	None	Fatigue
Morin et al. (182)	6	Within subject repeated measure time series	8 M	Physical education students	Sprint	Time	None	Fatigue (4 x 100 m sprints), Performance variables
Morin et al. (186)	7	Within subject repeated measure randomised crossover	10 M	Physically active	Run (3.3 m/s)	Dynamic	None	Stride rate (pref. $\bar{x}$=2.8 Hz), Contact time (pref. $\bar{x}$=0.24 s)
Morin et al. (209)	7	Within subject repeated measure time series	10 M	Experienced ultramarathon runners	Treadmill run (2.8 m/s)	Dynamic	None	Fatigue (24 hrs Ultra treadmill run)

Reference	QS	Study design	n, gender	Activity level	Movement	Stiffness	Normalisation	Factors
Morin et al. (208)	7	Within subject repeated measure pre/post	18 M	Experienced ultramarathon runners	Run (3.3 m/s)	Time	None	Fatigue (166 km Mountain Ultra)
Morin et al. (210)	7	Within subject repeated measure pre/post	11 M	Physical education students	Run (2.8, 5.6 m/s)	Dynamic	None	Fatigue (run sprint blocks, cycling sprint blocks)
Moritz and Farley (179)	5	Within subject repeated measure crossover	10 F	-	Bipedal hop (2.2 Hz)	Dynamic	None	Surface stiffness (unexpected change)
Oliver and Smith (198)	7	Between subject repeated measure	21 M (10 men, 11 boys)	Physically active	Bipedal hop (1.5, pref. – x̄=2.02-1.85 Hz)	Time	Body mass, leg length	Age, Muscle activity
Padua et al. (216)	7	Between subject	21 (11F, 11M)	Physically active	Bipedal hopping (pref.– x̄=2.3 Hz)	Dynamic	Body mass	Gender
Padua et al. (197)	8	Between and within subject repeated measure pre/post	21 (10F, 11M)	Physically active	Bipedal hop (pref. Hz)	Dynamic	Body mass	Muscle fatigue (1/3 BW BB squat)
Rabita et al. (176)	5	Within subject repeated measure time series	9 (3F, 6M)	Elite triathletes	Run (95% VO_{2max} – x̄=5.1 m/s)	Dynamic	None	Fatigue (exhaustive run), F_{ymax}, F_{ymin}, Performance variables
Rabita et al. (212)	6	Within subject repeated measure pre/post	12 M	Trained runners	Run (VO_{2max} – x̄=5.1 m/s)	Dynamic	None	Fatigue (maximum effort endurance run)
Slawinski et al. (213)	5	Within subject repeated measure pre/post	9 (2F, 7M)	10,000 m runners	Run (3.6 m/s)	Dynamic	None	Fatigue (2000 m time trial), C_R
Viale et al. (217)	7	Between subject repeated measure	32 M [19 opened foot, 13 closed foot]	Distance runners	Run (3.4-4.2 m/s)	Dynamic	None	Rear-to-forefoot angle
Williams III et al. (149)	8	Between subject	40 [20 HA (10F, 10M), 20 LA (12F, 8M)]	Runner	Run (3.4 m/s)	Dynamic, Inertial	Body mass	Arch height, Muscle activity

BB = barbell; *BF* = barefoot; *BW* = bodyweight; C_R = cost of running; *F* = female; F_{ymin} = minimum horizontal force; F_{ymax} = maximum horizontal force; F_{zmax} = maximum vertical force; *HA* = high arch; *Hz* = hertz; *LA* = low arch; *LT* = lactate threshold; *M* = male; *n* = sample size; *QS* = quality score; t_c = contact time; VO_{2peak} = peak volume of oxygen; VO_{2max} = maximum volume of oxygen.