

CHANGES IN LOWER EXTREMITY STIFFNESS WITH TRIATHLON SPECIFIC TRAINING

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Achilles tendon injuries are problematic severe injuries for triathletes. As an overuse injury, Achilles tendon injuries were proposed to be the result of a combination of risk factors, requiring measurements which incorporated multiple risk factors. Stiffness was identified to be a measure that was influenced by many of the risk factors for Achilles injury. In a one-year prospective study, 75 triathletes were followed to determine the association between measures of lower extremity stiffness and the risk of developing an Achilles injury. Triathletes who developed a new or reoccurring injury during the surveillance period had higher leg and knee to ankle stiffness ratio compared to Uninjured athletes. The influence of transitioning from cycling to running, on lower extremity stiffness were assessed. Transitioning from cycling caused an increase in ankle stiffness (ES=0.55) but a decrease in knee stiffness (ES=-0.38). Individual responses are likely to be important when assessing injury risk.

KEY WORDS: stiffness, triathlon, running, Achilles injury.

INTRODUCTION: Achilles tendon injuries are problematic for triathletes ranked as the most severe injury for club and development athletes (Vleck & Garbutt, 1998). Overuse injuries are the result of accumulated micro injury and are likely the result of a combination of risk factors. (Lorimer & Hume, 2014). Therefore, screening for Achilles injury risk should use measurements which are influenced by multiple identified risk factors. A review of the literature showed a number of risk factors associated with Achilles injury (Lorimer & Hume, 2014), many of which alter lower extremity stiffness during running or hopping tasks (Lorimer & Hume, 2016). Modelling the leg as a compressible spring using the spring-mass model and the joints as torsion springs allows the assessment of how the muscles, tendons, ligaments and joints work together in order to dissipate forces upon landing (McMahon & Cheng, 1990). Resistance to joint rotation and therefore 'leg spring' compression is represented as a single stiffness value. The study aimed to investigate whether stiffness of the lower extremity was associated with Achilles injury risk and how transitioning from cycling to running altered these stiffness measures.

METHODS: Seventy-five triathletes (32.6±9.1 y, 69.1±6.4 kg, 1.75±0.06 m, 45 males), volunteered for the research. All were currently professional or top-level age group (Olympic distance <2h 20 min/ 2h 40 min; male/female or Ironman distance <10h/ 11h 30 min; male/female in previous year) Olympic or long distance triathletes. 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. Triathletes were sent an injury reporting questionnaire every month for 12 months.

Athletes were marked with the SPRINZ lower body 3D motion analysis marker set (Lorimer, 2014). Following a 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). All accelerations were at 0.1 m/s and data were collected for the final 20 s of each two-minute block. Thirty-four triathletes returned for a transition test consisting of the graded run to give a

baseline stiffness level, followed by 30 minutes of self-regulated indoor cycling. Triathletes were instructed to cycle at an intensity similar to a sprint triathlon race in order to obtain the feeling they would experience when transitioning from the cycle to the run in a race setting. A one-minute standardised transition was given to change to running shoes before commencing up to 20 minutes running at 3.3, 3.7 or 4.2 m/s. Athletes selected the speed they wished to run at following the initial graded run. Kinematic and kinetic data were recorded for the last ten seconds of every minute.

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 hip and knee joint positions were determined using a custom-built MATLAB (*Optimization Toolbox*, Mathworks Inc.; Natick, MA, USA) constrained optimization program (Besier, Sturnieks, Alderson, & Lloyd, 2003). Joint angles and moments were calculated using Visual3D software (Visual3D™, C-motion Inc.; Rockville, MD, USA). Variables were averaged over 10 consecutive steps for the left leg for each individual as left and right leg showed similar results.

Leg, knee and ankle stiffness were calculated using equations 1-4 for the first half of stance from initial contact to maximal vertical ground reaction force.

$$K_{leg} = F_{max}/\Delta L \quad (1) \quad \Delta L = \Delta y + L_0(1 - \cos\theta) \quad (2)$$

$$\theta = \sin^{-1}(vt/2L_0) \quad (3) \quad k_{joint} = \Delta M/\Delta\theta \quad (4)$$

$$k_{knee/ankle} = k_{knee}/k_{ankle} \quad (5)$$

Where F_{max} = peak vertical force, ΔL = change in leg length, Δy = centre of mass displacement from double integration of force, L_0 = trochanterion height, θ = angle of leg swing; v = horizontal velocity = treadmill velocity, t_c = contact time, ΔM = change in joint moment, $\Delta\theta$ = change in joint angle.

Stiffness values were normalized to body weight before statistical analysis. Using an intention to treat analysis, athletes were divided into four groups based on injury status: three FirstAchilles (Achilles injury during surveillance period, no previous Achilles injury), four PriorAchilles (Achilles injury during the surveillance period, previous Achilles injury), nine PriorUninjured (prior Achilles injury, no injury during the surveillance period), and 23 Uninjured (no lower limb or lower back injuries during the surveillance period, no prior Achilles injury). Stiffness values of each group were compared with the Uninjured group using Cohen's d effect sizes with 95% confidence intervals. Differences between pre and post cycling were assessed using effect sizes with 90% confidence intervals due to mechanistic nature of the study (Hopkins, Marshall, Batterham, & Hanin, 2009).

RESULTS: The FirstAchilles and PriorAchilles showed small to moderate increases in leg stiffness at all running velocities compared to the uninjured group, while the PriorUninjured group had a small decrease. Analysis of the knee to ankle stiffness ratio (k_{knee}/k_{ankle}) indicated that while there was no difference between the PriorUninjured and Uninjured groups, both the PriorAchilles and FirstAchilles had moderately higher ratios compared to Uninjured (Figure 1). Following 30 minutes of self-paced indoor cycling, ankle stiffness showed a small increase compared to isolated running for the first four minutes (ES = 0.55 at 1 min, ES = 0.34 at 4 min). The knee showed a trivial change for the first two minutes and a small decrease in stiffness from three to five minutes (ES = -0.23 at 3 min, ES = -0.38 at 5 min). Leg stiffness was increased (ES = 0.63) for the first minute only. An analysis of the change scores for knee and ankle stiffness as a percentage of the pre-cycling average stiffness showed that individual responses were present (Figure 2). Thirty minutes of cycling may cause a small decrease in k_{knee}/k_{ankle} .

DISCUSSION: A novel measure of joint stiffness, k_{knee}/k_{ankle} , was determined to have potential for identifying triathletes at risk of developing Achilles injuries. Higher k_{knee}/k_{ankle} was observed for both individuals who developed their first Achilles injury compared to uninjured athletes and those who had a reoccurrence of injury. We suggest that k_{knee}/k_{ankle} may be useful, based on our preliminary laboratory tests, in applications such as identifying the effectiveness of

rehabilitation in injured triathletes. Many identified risk factors for Achilles injuries (Lorimer & Hume, 2014) have also been shown to change lower extremity stiffness. To understand how to modulate injury risk in high risk athletes, an understanding of how different variables alter stiffness may be important. The triathlon specific training variable, transitioning from cycling to running was investigated.

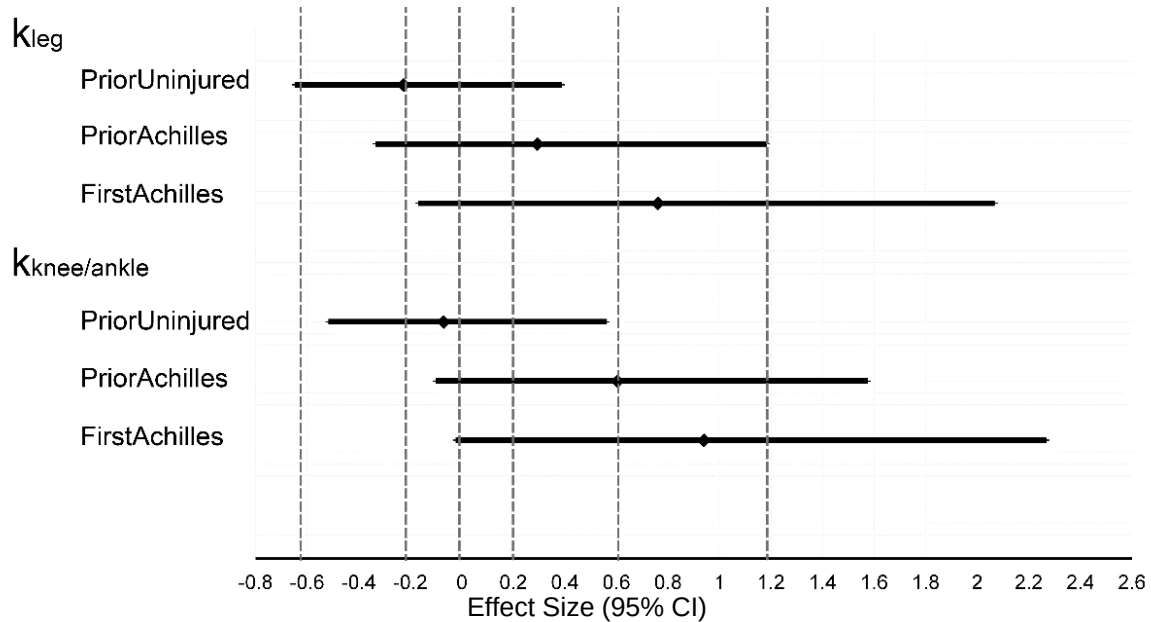


Figure 1: Forest plot of stiffness comparisons between injury groups and the Uninjured control.

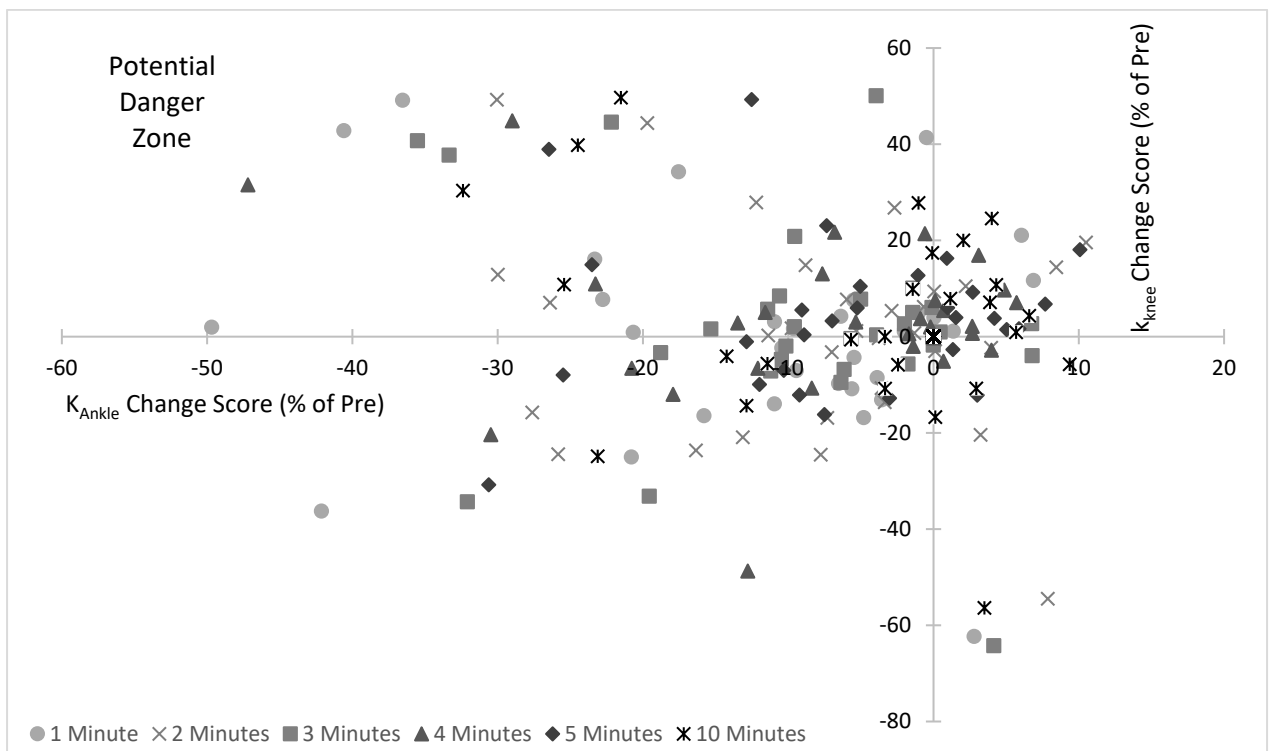


Figure 2: Knee and ankle stiffness change scores following 30 minutes of self-selected cycling as a percentage of pre-cycling average stiffness.

Transitioning from cycling to running resulted in an increase in ankle stiffness but a decrease in knee stiffness compared to isolated running. A smaller k_{knee}/k_{ankle} would result which is not associated with increased Achilles injury risk. However, individual analysis showed a number

of athletes presented with increased knee stiffness and decreased ankle stiffness which may increase Achilles injury risk in these athletes. Previous research has also shown that only some athletes present with altered muscle recruitment (Chapman, Vicenzino, Blanch, Dowlan, & Hodges, 2008), kinematics (Bonacci, Blanch, Chapman, & Vicenzino, 2010a) or both (Bonacci et al., 2010b) following cycling. Le Meur et al. (Le Meur et al., 2012) reported an increase in maximal vertical force and a decrease in contact time at 5% of the run off the bike. Decreasing contact time is associated with increased ankle stiffness (Kuitunen, Komi, & Kyrolainen, 2002) consistent with the group effects observed. While group results indicated a reduction in k_{knee}/k_{ankle} suggesting a reduced risk of Achilles injury, individual responses exhibiting increased knee stiffness without a corresponding increase in ankle stiffness may identify higher risk athletes. Changes in running mechanics and/or changes in muscle activity or recruitment could have contributed to the observed results.

CONCLUSION: This research identified a new measure of stiffness which has potential to identify triathletes who are at risk of developing Achilles tendon injuries. The training stimuli, running following cycling does not appear to be associated with increased risk of Achilles injury. However, individual responses may be more important. Further analysis of temporal, strike index and demographic factors may provide further insight into the mechanisms behind the different stiffness effects observed.

REFERENCES:

- Besier, T. F., Sturnieks, D. L., Alderson, J. A., & Lloyd, D. G. (2003). Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *Journal of Biomechanics*, 36(8), 1159-1168.
- Bonacci, J., Blanch, P., Chapman, A. R., & Vicenzino, B. (2010a). Altered movement patterns but not muscle recruitment in moderately trained triathletes during running after cycling. *Journal of Sports Sciences*, 28(13), 1477-1487.
- Bonacci, J., Green, D., Saunders, P. U., Blanch, P., Franettovich, M., Chapman, A. R., & Vicenzino, B. (2010b). Change in running kinematics after cycling are related to alterations in running economy in triathletes. *Journal of Science and Medicine in Sport*, 13(4), 460-464.
- Chapman, A. R., Vicenzino, B., Blanch, P., Dowlan, S., & Hodges, P. W. (2008). Does cycling effect motor coordination of the leg during running in elite triathletes? *Journal of Science and Medicine in Sport*, 11(4), 371-380.
- Girard, O., Millet, G., Slawinski, J., Racinais, S., & Micallef, J. (2013). Changes in running mechanics and spring-mass behaviour during a 5-km time trial. *International Journal of Sports Medicine*, 34(9), 832-840.
- Heiderscheit, B. C., Chumanov, E. S., Michalski, M. P., Wille, C. M., & Ryan, M. B. (2011). Effects of step rate manipulation on joint mechanics during running. *Medicine and Science in Sports and Exercise*, 43(2), 296-302.
- Hobara, H., Inoue, K., Gomi, K., Sakamoto, M., Muraoka, T., Iso, S., & Kanosue, K. (2010). Continuous change in spring-mass characteristics during a 400m sprint. *Journal of Science and Medicine in Sport*, 13(2), 256-261.
- Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, 41(1), 3-13.
- Kuitunen, S., Komi, P. V., & Kyrolainen, H. (2002). Knee and ankle joint stiffness in sprint running. *Medicine and Science in Sports and Exercise*, 34(1), 166-173.
- Le Meur, Y., Dorel, S., Rabita, G., Bernard, T., Brisswalter, J., & Hausswirth, C. (2012). Spring-mass behavior and electromyographic activity evolution during a cycle-run test to exhaustion in triathletes. *Journal of Electromyography and Kinesiology*, 22(6), 835-844.
- Lorimer, A. V. (2014). *Evaluating stiffness of the lower limb 'springs' as a multifactorial measure of Achilles tendon injury risk in triathletes* (Doctoral thesis, Auckland University of Technology).
- Lorimer, A. V., & Hume, P. A. (2014). Achilles tendon injury risk factors associated with running. *Sports Medicine*, 44(10), 1459-1472. doi: 10.1007/s40279-014-0209-3
- Lorimer, A.V. & Hume, P.A. (2016).
- McMahon, T. A., & Cheng, G. C. (1990). The mechanics of running: How does stiffness couple with speed? *Journal of Biomechanics*, 23(S1), 65-78.
- Rabita, G., Couturier, A., & Lambertz, D. (2011). Intrinsic ankle and hopping leg-spring stiffness in distance runners and aerobic gymnasts. *International Journal of Sports Medicine*, 32(7), 552-558.
- Vleck, V.E., & Garbutt, G. (1998). Injury and training characteristics of male elite, development squad, and club triathletes. *International Journal of Sports Medicine*, 19 (1), 38-42.

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