Achilles Tendon Mechanical Properties After Both Prolonged Continuous Running and Prolonged Intermittent Shuttle Running in Cricket Batting

Laurence Houghton, Brian Dawson, and Jonas Rubenson
University of Western Australia

Effects of prolonged running on Achilles tendon properties were assessed after a 60 min treadmill run and 140 min intermittent shuttle running (simulated cricket batting innings). Before and after exercise, 11 participants performed ramp-up plantar flexions to maximum-voluntary-contraction before gradual relaxation. Muscle-tendon-junction displacement was measured with ultrasonography. Tendon force was estimated using dynamometry and a musculoskeletal model. Gradients of the ramp-up force-displacement curves fitted between 0–40% and 50–90% of the preexercise maximal force determined stiffness in the low- and high-force-range, respectively. Hysteresis was determined using the ramp-up and relaxation force-displacement curves and elastic energy storage from the area under the ramp-up curve. In simulated batting, correlations between tendon properties and shuttle times were also assessed. After both protocols, Achilles tendon force decreased (4% to 5%, \( P < .050 \)), but there were no changes in stiffness, hysteresis, or elastic energy. In simulated batting, Achilles tendon force and stiffness were both correlated to mean turn and mean sprint times (\( r = –0.719 \) to –0.830, \( P < .050 \)). Neither protocol resulted in fatigue-related changes in tendon properties, but higher tendon stiffness and plantar flexion force were related to faster turn and sprint times, possibly by improving force transmission and control of movement when decelerating and accelerating.

**Keywords:** change of direction, fatigue, hysteresis, stiffness, ultrasonography

In cyclic locomotion, such as running or turning, the Achilles tendon stores and returns elastic energy during a stretch-shortening cycle of the muscle-tendon unit. As a result, less work is required by the muscle fiber and economy of movement is improved.\(^1,2\) Thus, altered tendon stiffness may influence locomotor performance, but the exact mechanisms remain unclear. In theory, a decrease in tendon stiffness will increase its ability to store elastic energy for a given force level, but may also compromise optimal muscle strain and velocity, and therefore reduce muscle efficiency.\(^3\) Interestingly, stiffer tendons have recently been related to superior running economy\(^4\) providing indirect evidence of this tradeoff. Therefore, it is possible that control and economy of human movement might be compromised if Achilles tendon mechanical properties change during fatigue.\(^5\)

Changes in isolated animal and human tendons have been observed ex vivo after repeated cyclic loading.\(^6,7\) Research has also observed acute changes in tendon properties in vivo after exercise in humans.\(^8\) For example, decreases in tendon stiffness have been demonstrated after repeated (6–50 repetitions), high strain (> 6%), long duration (6–15 s) maximal-voluntary-isometric contractions.\(^5,8–10\) Conversely, repeated short duration (< 3 s) contractions (submaximal and maximal effort) appear to have minimal effect on tendon stiffness.\(^5,11\) Peltonen et al\(^12\) observed no changes in Achilles tendon stiffness after two-footed hopping to exhaustion (1150–2600 jumps, ~15 min), indicating that longer stretch-shortening cycle protocols may not induce the same changes in tendon mechanical properties as short duration isometric contractions. While these previous studies have been instrumental to our understanding of tendon mechanics, the fatigue protocols were short, often required only isometric contractions, and focused on continuous, steady-state contraction protocols.\(^8\) Nevertheless, the findings of Peltonen et al\(^12\) suggested a trend for a greater decrease in stiffness as more jumps were completed (\( r = –0.527, P = .118 \)). Therefore, it could be that more prolonged stretch-shortening cycle exercise (ie, > 60 min) leads to changes in Achilles tendon stiffness.

Furthermore, the effect of prolonged exercise on tendon hysteresis in vivo is unknown. Hysteresis is important because it reflects how much stored elastic energy is dissipated as heat during recoil of a tendon\(^13\) and may also affect muscle fiber strain and velocity profiles. Previous
research has observed decreases in hysteresis after ex vivo cyclical activity and in vivo short duration stretch protocols, yet it is not known if hysteresis changes as a result of prolonged continuous or intermittent running. Many team sports consist of intermittent running with repeated deceleration, acceleration, and turning eg, soccer, cricket, rugby, and field hockey. For example, in one-day cricket, a batsmen typically covers about 5500 m in 2 h when scoring more than 100 runs in an innings, but only 12% of this distance will be run at high intensity (> 3.89 m·s⁻¹). Surprisingly, little research has explored how the Achilles tendon is affected by prolonged activity that includes acceleration, deceleration, and/or change of direction, and reflects the demands of everyday movement or sports performance. For example, it is not known whether decrements in intermittent shuttle run times observed (as previously observed during prolonged, simulated batting) are accompanied by changes in Achilles tendon properties.

In summary, the primary aim of this study was to assess Achilles tendon mechanical properties before and after (1) prolonged continuous running (60 min treadmill run) and (2) prolonged, intermittent shuttle running with straight line sprinting and turning (using a 140 min simulated cricket batting innings). Each protocol simulated different durations and modes of prolonged running activity and so direct comparison was not intended per se. It was hypothesized that both running protocols would result in decreased Achilles tendon force, stiffness, hysteresis, and elastic energy storage, and an increase in muscle-tendon-junction displacement. A secondary aim was to investigate the relationships between Achilles tendon mechanical properties and intermittent shuttle running performance during simulated batting. It was hypothesized that higher Achilles tendon force and stiffness would be related to faster intermittent shuttle running performance during simulated batting.

Method

Participants

For both exercise protocols, the same male cricket batsmen (n = 11) were recruited from local clubs (mean ± SD: 22 ± 3 y, 183 ± 5 cm, 80.7 ± 6.4 kg). Participants were conditioned for cricket, but did not train for distance running. All protocols of the study were approved by the University of Western Australia’s Human Research Ethics Committee. Participants were given full details of the demands and procedures of the study before providing written informed consent.

Study Design

All testing started at 0800 in an indoor laboratory. In the first part of the study, participants were familiarized with procedures and, two days later, Achilles tendon mechanical properties were assessed before and after a 60 min treadmill run. In the second part of the study (4–5 weeks later), the same participants were accustomed to a simulated batting innings. At least seven days later, Achilles tendon properties were assessed before and after the simulated batting innings.

Achilles Tendon Properties

Previously, a minimum of 270 loading cycles was demonstrated to stabilize Achilles tendon mechanical properties and so participants underwent a 3 min light-intensity jog (467 ± 28 steps) before testing. Next, participants lay prone on a dynamometer (Biodex System 3, 835-220, Shirley, N.Y., USA) with right ankle restricted to 90° (neutral), but, for comfort, slight knee flexion (~5° to 10°) was permitted. The lateral malleolus of the right ankle was aligned with the center of rotation of the dynamometer arm. To minimize joint rotation, the foot was fixed to the footplate with additional strapping. Reflective markers were attached (medial malleolus, heel, medial tibial condyle, and first metatarsal of the foot) to allow determination of relative ankle angle change from the video footage (25 Hz, Sony DCR-HC52E, Japan). Participants then performed four submaximal and two maximal, isometric, plantar flexion, contractions to further ensure the effects of Achilles tendon preconditioning were eliminated.

Next, participants performed a 5 s ramp isometric plantar flexion to maximum-voluntary-contraction, immediately followed by a five second gradual relaxation. Participants completed these “ramp-relaxation” contractions in time with a custom-made audio track and a live display of the torque-time graph (Spike II software v7.02a, Cambridge Electronic Design, UK). Each ramp-relaxation contraction was separated by 90 s of rest. Throughout the ramp-relaxation contractions, the muscle-tendon-junction of the right medial gastrocnemius was visualized using a B-mode ultrasound probe firmly strapped to the calf (6–7 MHz, 70–80 frames per second, 60 mm scanning length, Echoblaster 128 EXT-1Z, Telemed Ltd., Lithuania). The skin surrounding the probe was marked with a pen to ensure the probe was positioned identically after exercise. The start of the ultrasound imaging was denoted by a synchronization pulse (collected in Spike II software) which also turned on a light emitting diode that was visible on the video footage.

During the ramp-relaxations there was 7.5 ± 2.1° of plantar flexion at maximum-voluntary-contraction. As a result, the observed muscle-tendon-junction displacement was due to a combination of tendon stretch and change in ankle angle. Therefore, a passive rotation test was used to determine the relationship between ankle angle and muscle-tendon-junction displacement. The dynamometer passively rotated the ankle joint (five degrees per second) with ultrasound images captured on the fourth rotation. Digitization of the reflective marker position demonstrated that the ankle was rotated from 7.3 ± 2.2° dorsiflexion to 14.1 ± 2.4° plantar flexion. For each participant, a linear regression
(R^2 = .96 ± 0.04) determined the relationship between ankle angle and muscle-tendon-junction displacement (between -4.5 ± 2.0 mm and 11.0 ± 2.5 mm). These linear regressions allowed ankle rotation to be accounted for in the muscle-tendon-junction displacement during the ramp-relaxations.

Preamplified, double differential surface electromyography (EMG) was used to measure activity of the right medial gastrocnemius and tibialis anterior (MotionLabs, MA 100). The EMG electrodes (Cleartrace 1700, ConMed, Utica, USA; interelectrode distance: 25 mm) were secured for the duration of the run and simulated batting. The EMG (and torque signals) were collated and processed in Spike II software (version 7.02a, Cambridge Electronic Design, UK, 2000 Hz) via an analog-digital converter (ADC-12, 1401, Cambridge Electronic Design, UK). All EMG data were processed with a 2nd order, zero-lag, Butterworth bandpass filter (20 Hz to 500 Hz) and a mains notch filter. The filtered EMG was rectified and smoothed with a root-mean-squared algorithm (0.3 s intervals). All EMG signals were presented as percentage of maximum activation during the testing session. During the ramp-relaxation contractions the intraindividual timing for reaching maximum medial gastrocnemius activation was consistent from pre to post exercise (pre vs post: 5.125 ± 0.609 s and 4.963 ± 0.619 s; P = .288, intraclass correlation coefficient = 0.78; coefficient of variation = 6.7%).

After the ramp-relaxation contractions (pre- and posttest), participants completed two, 3 s, isometric ramp dorsiflexions to maximum-voluntary-contraction separated by 90 s. These trials enabled determination of co-contraction of the tibialis anterior in the ramp-relaxations. Co-contraction of the dorsiflexors occurred (~15% activation) during the ramp-relaxation contractions and so the net dynamometer torque was a combination of muscle plantar flexion torque (+ve) and dorsiflexion torque (−ve). Therefore, an estimation of dorsiflexion torque during the ramp-relaxations was required to more accurately determine the muscle plantar flexion torque. In the ramp-up isometric dorsiflexions, the relationship between tibialis anterior EMG and dorsiflexion torque was fitted with a linear regression (R^2 > .90). These linear regressions allowed estimation of dorsiflexion torque from the tibialis anterior EMG signal in the ramp-relaxations. The estimated dorsiflexion torque was then summed with the net dynamometer torque to give an estimation of torque produced by the plantarflexors. Also, the torque caused by mass of the resting lower limb and dynamometer attachments was subtracted from the overall torque to provide a net torque.

The Achilles tendon moment arm was determined from the slope of the linear regression equation fitted to the muscle-tendon-junction displacement-ankle angle graph from the passive rotation test. A passive test was conducted in the running and batting trials and so a mean moment arm was used. Moment arm (MA) and plantar flexor torque (Tpf) were then used to estimate Achilles tendon force (F):

\[ F = \frac{T_{pf}}{MA} \]

In each ramp-relaxation, the tendon force at 10% increments of the pretest maximum tendon force were found with a custom macro (Visual Basic v 6.5, Microsoft 1987–2006) and matched to the corresponding frame on the ultrasound image. In each of these frames the displacement of the muscle-tendon-junction (Figure 1) was measured using ImageJ software (v1.43). A thin piece of translucent tape was fixed to the skin so that a shadow was cast on the ultrasound image and verified that the position of the ultrasound probe did not move during contraction (Figure 1). High-force-range tendon stiffness (N∙mm⁻¹) was calculated from the slope of the linear regression equation (R^2 = .96 ± 0.08) fitted to the force-displacement graph between 50% and 90% of maximum Achilles tendon force on the day of testing. Similarly, low-force-range stiffness was calculated between zero

---

**Figure 1** — Examples of the ultrasound images taken in one participant. The point where the two black lines meet highlights the positions of the muscle-tendon junction: (A) when relaxed, (B) at maximum-voluntary-contraction.
and 40% of maximum Achilles tendon force \( (R^2 = .96 \pm 0.03) \), since this force range has previously been suggested to be more applicable to running.\(^2\) Hysteresis (%) was calculated as the area of the loop formed between the ramp-up and relaxation force-displacement curves expressed as a percentage of the area below the ramp-up curve.\(^3\) Elastic energy storage (J) was calculated as the total area below the ramp-up curve.\(^1\) A ramp-relaxation was not used in analysis if the curve was not a smooth ramp-up and relaxation (ie, if there were multiple peaks in torque) and if the participant did not reach at least 80% maximum torque in the day of testing. For both pre- and postexercise, stiffness, hysteresis, and elastic energy storage were presented as the mean of three ramp-relaxation contractions which satisfied the above criteria (with the exception of one participant’s post batting trial in which only two ramp-relaxation contractions were available).

**Continuous Treadmill Run**

In the first part of this study, the treadmill run (Trimline 2600, Hebb Industries Inc., Texas, USA) was completed at a pace which the participant felt could easily be maintained for 60 min and which resulted in 9250 ± 323 steps (ie, similar step frequency). In this manner both total exercise duration and loading cycles were controlled in the run. Moreover, it was ensured that the running speed (2.2 ± 0.1 m s\(^{-1}\)) did not result in high cardiovascular strain (ie, at an intensity that did not result in lactate accumulation, thus minimizing the influence of physiological and/or central fatigue). The 60 min run was completed in an indoor laboratory \( (19.0 \pm 0.5^\circ C, 61 \pm 8\% \) relative humidity). In the second part of this study, the batting simulation was completed at a nearby outdoor facility on a synthetic surface \( (19.0 \pm 2.4^\circ C, 48 \pm 13\% \) relative humidity). Pre- and postexercise, stiffness, hysteresis, and elastic energy storage were presented as the mean of three ramp-relaxation contractions which satisfied the above criteria (with the exception of one participant’s post batting trial in which only two ramp-relaxation contractions were available).

**Prolonged, Intermittent Shuttle Running**

In the second part of this study, the batting simulation was completed at a nearby outdoor facility on a synthetic surface \( (19.0 \pm 2.4^\circ C, 48 \pm 13\% \) relative humidity). Preconditioning of the Achilles tendon had already occurred before the ramp-relaxation contractions. However, to replicate typical prematch routine, participants also performed a standardized warm-up before simulated batting (~8 min of light intensity shuttle runs and dynamic stretching). A running warm-up protocol of similar duration has previously been shown to have no effect on Achilles tendon mechanical properties.\(^2\) Briefly, the simulated batting innings was composed of six consecutive, 21 min batting stages. In stages one, three and five, the batsman completed all running at a “self-selected cruise” pace, whereas in stages two, four and six, all running was completed at maximal speed. Therefore, using an infra-red, electronic timing system (Swift, Australia), running-between-the-wickets performance was assessed at the five meters into and the five meters out of the turn.\(^2\) Across stages two, four, and six running-between-the-wickets performance was reported as the mean sprint time and mean turn time. Overall, the simulated batting protocol was reported as the mean sprint time and mean turn time.

Data Analysis

The test-retest statistics suggested moderate to high reliability for the measures of Achilles tendon mechanical properties (Table 1). Paired \( t \) tests were used to compare Achilles tendon mechanical properties before and after exercise in Microsoft Excel (2003), since direct comparisons between protocols were not intended. In simulated batting, Pearson’s product moment correlations \( (r) \) were

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Repeatability statistics for the Achilles tendon mechanical properties (n = 44 data pairs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TE</td>
</tr>
<tr>
<td>Achilles tendon force (N)</td>
<td>95</td>
</tr>
<tr>
<td>Low-force-range stiffness (N-mm(^{-1}))</td>
<td>29</td>
</tr>
<tr>
<td>High-force-range stiffness (N-mm(^{-1}))</td>
<td>56</td>
</tr>
<tr>
<td>Hysteresis (%)</td>
<td>4.8</td>
</tr>
<tr>
<td>Elastic energy (J)</td>
<td>3.8</td>
</tr>
<tr>
<td>Maximum muscle-tendon junction displacement (mm)</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Note. CV = coefficient of variation, ICC = intraclass correlation coefficient, TE = typical error.
determined between resting Achilles tendon mechanical properties and running-between-the-wickets performance (PASW statistics v18.0.0). Running-between-the-wickets times were incomplete for one participant because of technical complications so were not included in the correlation analysis. All values are mean ± standard deviation. Statistical significance was accepted at \( P < .050 \).

**Results**

Tendon force was the only Achilles property that changed after the 60 min run with a significant decrease reported \( (P = .033, \text{Table 2}) \). There were no changes in Achilles tendon low-force-range stiffness, high-force-range stiffness, hysteresis, elastic energy storage, or maximum muscle-tendon-junction displacement after the run \( (P = .394 \text{ to } .870, \text{Table 2}) \). Furthermore, in both the ramp-up and relaxation contraction there were no pre–post changes in muscle-tendon-junction displacement at any of the 10% increments in tendon force \( (n = 10, P = .239 \text{ to } .977, \text{ Figure 2}) \). After the 60 min run (and simulated batting) the force at maximal-voluntary-contraction decreased but both pre- and postexercise tendon stiffness were calculated at matched force values relative to the pretest maximal force. As a result, the point of absolute maximal force \( (> 90\% \text{ maximal-voluntary-contraction}) \) in the postexercise test has been included in Figure 2 to close the hysteresis loop. In addition, note that data from participant 10 is not included in Figure 2 because of unavailability of tendon force-displacement curves for the relaxation phase. Percentage tibialis anterior and medial gastrocnemius activation were both similar before and after the run \( (P = .201 \text{ and } .685, \text{ respectively, Table 2}) \). Mean ratings of perceived exertion \( (13 \pm 1, \text{Figure 2}) \).

**Figure 2** — Muscle-tendon junction displacement at 10% force increments (relative to preexercise peak force) in ramp to maximal-voluntary-contraction (diamonds) and relaxation (squares) both before (dotted line) and after (continuous line) (A) a 60 min treadmill run and (B) prolonged, intermittent shuttle running (simulated batting innings). For clarity, error bars (standard deviation) have only been included for muscle-tendon-junction displacement.
Table 2  Achilles tendon mechanics and muscle electromyography before and after the 60 min continuous run and prolonged, intermittent shuttle running (simulated batting)

<table>
<thead>
<tr>
<th></th>
<th>60 Min Run</th>
<th>%Change</th>
<th>Simulated Batting</th>
<th>%Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td></td>
<td>Pre</td>
</tr>
<tr>
<td>Achilles tendon force (N)</td>
<td>5267 ± 1318</td>
<td>5053 ± 1468*</td>
<td>−4.2</td>
<td>5009 ± 1277</td>
</tr>
<tr>
<td>Low-force-range stiffness (N-mm⁻¹)</td>
<td>261 ± 84</td>
<td>269 ± 112</td>
<td>2.7</td>
<td>242 ± 89</td>
</tr>
<tr>
<td>High-force-range stiffness (N-mm⁻¹)</td>
<td>422 ± 172</td>
<td>394 ± 148</td>
<td>−7.2</td>
<td>365 ± 144</td>
</tr>
<tr>
<td>Hysteresis (%)</td>
<td>26.2 ± 9.4</td>
<td>28.6 ± 9.7</td>
<td>8.6</td>
<td>22.5 ± 6.7</td>
</tr>
<tr>
<td>Elastic energy (J)</td>
<td>38.1 ± 14.4</td>
<td>37.2 ± 15.8</td>
<td>−2.4</td>
<td>37.7 ± 11.7</td>
</tr>
<tr>
<td>Maximum muscle-tendon junction displacement (mm)</td>
<td>15.9 ± 2.9</td>
<td>15.8 ± 2.3</td>
<td>−0.8</td>
<td>17.0 ± 2.6</td>
</tr>
<tr>
<td>% Medial gastrocnemius activation</td>
<td>92.9 ± 5.4</td>
<td>93.9 ± 3.8</td>
<td>1.0</td>
<td>92.7 ± 5.9</td>
</tr>
<tr>
<td>% Tibialis anterior activation</td>
<td>12.9 ± 7.4</td>
<td>16.4 ± 8.6</td>
<td>21.8</td>
<td>16.3 ± 8.3</td>
</tr>
</tbody>
</table>

*Significantly different from pre, \( P < .050 \). *For simulated batting sample, \( n = 10 \).
After batting, tendon force was the only Achilles tendon property to significantly decrease ($P = .001$, Table 2) and there were no changes in Achilles tendon low-force-range stiffness, high-force-range stiffness, hysteresis, elastic energy storage or the maximum muscle-tendon-junction displacement ($P > .050$, Table 2). Similarly, after batting there were no differences in muscle-tendon-junction displacement at all increments of submaximum force ($P = .170$ to $.825$, Figure 2). Percentage tibialis anterior and medial gastrocnemius activation were both similar before and after simulated batting ($P = .112$ and $.806$, respectively, Table 2). Mean running-between-the-wickets times (both sprint time and turn time), heart rate and ratings of perceived exertion all increased from simulated batting Stage 2–6, demonstrating increasing fatigue and physiological strain ($P < .050$, Table 3).

Higher Achilles tendon force and stiffness were both related to faster intermittent shuttle running performance during simulated batting. Baseline maximum Achilles tendon force was negatively correlated with mean sprint time ($r = -0.819$, $P = .004$, Figure 3A) and turn times ($r = -0.719$, $P = .019$, Figure 3B). Baseline low-force-range stiffness was negatively correlated with mean sprint time ($r = -0.719$, $P = .019$, Figure 3C) and turn times ($r = -0.830$, $P = .003$, Figure 3D). Similarly, baseline high-force-range stiffness was strongly correlated with mean sprint time ($r = -0.649$, $P = .042$).

### Discussion

It was hypothesized that both the 60 min run and simulated cricket batting would result in decreased Achilles tendon force, stiffness, hysteresis, and elastic energy storage, and an increase in muscle-tendon-junction displacement. However, the only significant change was a decrease in Achilles tendon force (4% to 5%) for both protocols. The secondary aim of this study was to investigate the relationship between Achilles tendon mechanical properties and intermittent shuttle running performance. In agreement with the second hypothesis, greater Achilles tendon stiffness (particularly in the low force range) and ability to produce higher plantar flexion force were correlated to faster sprinting and turning (running-between-the-wickets times) in simulated batting.

Although direct comparison between the two protocols was not intended, maximum Achilles tendon force decreased to a similar extent after both the run and simulated batting (4% to 5%), suggesting that both exercises induced comparable muscular fatigue. Furthermore, in the simulated batting trial, physical fatigue was demonstrated by a slowing in running-between-the-wickets times from Stage 2–6. In the 60 min run and simulated batting, mean heart rates, and ratings of perceived exertion suggested that the overall workload was of moderate to high intensity.

Despite physical fatigue, Achilles tendon mechanical properties (low-force-range stiffness, high-force-range stiffness, hysteresis, and elastic energy) did not change after the run. It is estimated that the running pace (~2 m·s⁻¹) induced less than 5.5% tendon strain.³ Exercise induced change in Achilles tendon stiffness has only been demonstrated after high force, long duration contractions, such as 15 s.¹⁰ Therefore, the overall findings of the current research confirm that cyclic, submaximal, short duration contractions which do not induce more than 6% strain are unlikely to lead to a change in a tendon’s force-displacement relationship—particularly if the tendon is preconditioned in warm-up.⁵,⁸,²⁰

Achilles tendon mechanical properties (low-force-range stiffness, high-force-range stiffness, hysteresis, and elastic energy) also remained unchanged after the prolonged, intermittent shuttle running of the simulated batting innings. Previously, Noakes and Durandt¹⁹ suggested that fatigue in prolonged cricket batting may be better explained with a “biomechanical” model rather than traditional fatigue paradigms. A biomechanical model suggests that fatigue in cricket batting may be related to altered mechanical properties of the lower-limb tendons as a result of the prolonged, intermittent accelerating, sprinting, decelerating and turning.¹⁹ Although fatigue was demonstrated after simulated batting (increased running-between-the-wickets times and decreased plantar flexion force), current findings suggest that a biomechanical model may not be relevant.

The time taken to begin assessment postexercise might explain the finding of no overall changes in Achilles tendon properties after simulated batting and the 60 min run. It is feasible that changes in mechanical properties were present immediately after both protocols, but

### Table 3  Running times and physiological responses in the prolonged, intermittent shuttle running (simulated batting)

<table>
<thead>
<tr>
<th></th>
<th>Stage 2</th>
<th>Stage 4</th>
<th>Stage 6</th>
<th>Overall Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean sprint time (s)</td>
<td>0.79 ± 0.04</td>
<td>0.80 ± 0.04*</td>
<td>0.81 ± 0.05*</td>
<td>0.80 ± 0.04</td>
</tr>
<tr>
<td>Mean turn time (s)</td>
<td>2.25 ± 0.09</td>
<td>2.28 ± 0.13</td>
<td>2.31 ± 0.12*</td>
<td>2.28 ± 0.11</td>
</tr>
<tr>
<td>Heart rate (beats per min)</td>
<td>137 ± 16</td>
<td>145 ± 15*</td>
<td>151 ± 16*</td>
<td>136 ± 15</td>
</tr>
<tr>
<td>Rating of perceived exertion</td>
<td>12 ± 2</td>
<td>14 ± 2*</td>
<td>16 ± 3*</td>
<td>13 ± 1</td>
</tr>
</tbody>
</table>

*Significantly different from stage 2, $P < .050$. Note that n = 10 for the sprint and turn times.
stabilized to baseline values before assessment. However, reduced Achilles tendon stiffness has been observed up to 40 min after six, 8 s maximum-voluntary-isometric-contractions, indicating that our seven to 11 min window may have been sufficient to observe any exercise induced changes. Nevertheless, it is not known if immediate or delayed (e.g., 24 h to 72 h) changes in Achilles tendon mechanical properties occur after prolonged exercise.

Although there were no changes in Achilles tendon properties after simulated batting, at baseline, higher low-force-range stiffness and high-force-range stiffness were both related to faster straight-line sprinting and higher low-force-range stiffness was related to faster turning. Arampatzis et al. reported greater Achilles tendon stiffness in high-economy versus low-economy distance runners. Similarly, Fletcher et al. demonstrated that greater Achilles tendon stiffness (at high and low force ranges) was related to more economical long distance running. Although running economy was not assessed per se, Kubo et al. found that lower Achilles tendon stiffness was correlated to faster 5000 m running times. However, these previous findings relate to prolonged, continuous running without intermittent sprinting and turning. The current finding suggests that high Achilles tendon stiffness in a low force range (arguably of greater physiological relevance than that at high force range) could be of particular advantage for fast, intermittent turning over a prolonged duration. It is possible that a stiffer Achilles tendon improves control of movement when decelerating into a turn and allows more effective transmission of force when sprinting and accelerating out of a turn.

In simulated batting, faster straight-line-sprint and turn times were also related to greater Achilles tendon force (plantar flexor strength). Arampatzis et al. demonstrated a greater plantar flexor strength in high- versus low-economy long distance runners. Although it is not possible to make direct comparison, it could be that high plantar flexor strength also contributes toward more effective and economical human movement when performing prolonged, intermittent shuttle running. In particular, high plantar flexor strength may improve control when decelerating and accelerating during turns. Previous research has not consistently observed a relationship between leg strength and turn performance. However, performance has typically been assessed over less than 10 repeated turns across a short time period, in contrast to the 20 full-speed turns in the prolonged simulated batting protocol. Although higher Achilles tendon stiffness and force were related to faster intermittent shuttle running performance, it is cautioned that optimal Achilles tendon mechanical properties exist such that increasing stiffness beyond a critical point could be detrimental to muscle efficiency.

In conclusion, after a 60 min treadmill run and a prolonged, intermittent shuttle run (simulated batting) there was a fatigue-related decrease in maximum Achilles tendon force.

**Figure 3** — Correlations between baseline maximum Achilles tendon force and (A) mean sprint time; and (B) mean turn time, in the simulated batting innings. Also correlations between baseline low-range-force stiffness and (C) mean sprint time; and (D) mean turn time. Note that the y-axis scales do not start at zero.
tendon force, but no changes in Achilles tendon mechanical properties. Interestingly, participants with the ability to produce greater isometric plantar flexion force and with higher Achilles tendon stiffness tended to have faster running-between-the-wicket times. It is possible that high Achilles tendon stiffness and ability to produce high plantar flexion force improve both force transmission and control of movement when decelerating and accelerating.

Acknowledgments

We acknowledge the West Coast Eagles Football Club for loan of the timing gates in this research. We also wish to acknowledge the efforts of all participants and both Gabriel Choong and Ander Rodoreda for their invaluable assistance with data collection. This research was carried out while the corresponding author was in receipt of a University International Stipend and an Endeavour International Postgraduate Research Scholarship at the University of Western Australia.

References