Influence of Neuromuscular Fatigue on Accelerometer Load in Elite Australian Football Players

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Purpose: To determine the impact of neuromuscular fatigue (NMF) assessed from variables obtained during a countermovement jump on exercise intensity measured with triaxial accelerometers (load per minute [LPM]) and the association between LPM and measures of running activity in elite Australian Football. Methods: Seventeen elite Australian Football players performed the Yo-Yo Intermittent Recovery Test level 2 (Yo-Yo IR2) and provided a baseline measure of NMF (flight time:contraction time [FT:CT]) from a countermovement jump before the season. Weekly samples of FT:CT, coaches' rating of performance (votes), LPM, and percent contribution of the 3 vectors from the accelerometers in addition to high-speed-running meters per minute at >15 km/h and total distance relative to playing time (m/min) from matches were collected. Samples were divided into fatigued and nonfatigued groups based on reductions in FT:CT. Percent contributions of vectors to LPM were assessed to determine the likelihood of a meaningful difference between fatigued and nonfatigued groups. Pearson correlations were calculated to determine relationships between accelerometer vectors and running variables, votes, and Yo-Yo IR2 score. Results: Fatigue reduced the contribution of the vertical vector by (mean ± 90% CI) –5.8% ± 6.1% (86% likely) and the number of practically important correlations. Conclusions: NMF affects the contribution of individual vectors to total LPM, with a likely tendency toward more running at low speed and less acceleration. Fatigue appears to limit the influence of the aerobic and anaerobic qualities assessed via the Yo-Yo IR2 test on LPM and seems implicated in pacing.

Keywords: team sport, pacing, activity profile

Monitoring both fatigue and capacity is important in high-performance environments to optimize the training stimulus and minimize unplanned fatigue.1 It has previously been suggested that capacity (ie, performance on a fitness test) and fatigue work in opposition to determine physical performance, and this model has been demonstrated to apply to elite Australian Football.2,3 Specifically, performance in elite Australian Football measured via coaches' votes has been shown to be influenced by both capacity (assessed by Yo-Yo Intermittent Recovery Test level 2 [Yo-Yo IR2]) and neuromuscular fatigue (NMF; quantified via flight time:contraction time [FT:CT] from a countermovement jump).3–6 Recently, load per minute (LPM) calculated from triaxial accelerometers sampling at 100 Hz has been used as an activity-profile (ie, exercise-intensity) measure in elite Australian Football.1 That research demonstrated that for a given LPM, players are perceived by coaches to have performed relatively poorly when playing with preexisting NMF.3 While it appears that LPM is therefore a useful measure of exercise intensity in elite Australian Football players and that its relationship with coach perception of performance is influenced by NMF status (assessed by a countermovement jump), the precise mechanism responsible for the perceived poor performance when playing a match with preexisting NMF is unknown. While it is unclear whether NMF measured by alterations in FT:CT is due to centrally or peripherally mediated factors, acute mechanisms such as metabolic disturbance can be excluded,3–6 and so the influence on coach rating could be due to a modification in neuromuscular function resulting in less efficient movement.7–12 Although such an alteration may not result in changes to parameters such as total distance, the use of high-sample-rate (100 Hz) sensors such as accelerometers that allow the detection of movement in 3 planes could enable quantification of subtle changes in movement patterns3,13,14 It may be that these subtle movement changes are critical to elite Australian Football performance.

Therefore, the purpose of this research was to determine if NMF, quantified by the ratio of FT:CT from a countermovement jump, resulted in any practically important modifications to the relative contributions of the individual mediolateral (x), anteroposterior (y), and vertical (z) accelerometer vectors to total LPM. In addition, this research aimed to explore whether there were
any practically meaningful changes to the relationships between measures of running intensity and the individual accelerometer vectors as the result of preexisting NMF.

**Methods**

Subjects
Seventeen elite Australian Football players from the same team with a mean (± SD) height, mass, and age of 187.6 ± 7.3 cm, 86.5 ± 8.7 kg, and 22.3 ± 3.3 years, respectively, participated in this study. Ethical approval from the university research ethics committee and informed consent were gathered before the commencement of the research.

Design
A sample was determined as the same player having provided all of the following: Yo-Yo IR2 test before the start of the season, match LPM, high-speed-running (HSR) meters per minute at >15 km/h, total distance relative to playing time (m/min), FT:CT ratio (before the upcoming match), and coaches votes from any of the 22 matches of the same competitive season. In all, 37 samples (range of 1–4 samples per player) were obtained.

Methodology
NMF was assessed according to previously established protocols using FT:CT, which is both valid and reliable in elite Australian Football players.3–6 Briefly, FT:CT was calculated from a body-weight countermovement jump for maximum height, performed on a force plate (400 Series, Fitness Technology, Adelaide, Australia), where FT represents the time from toe-off until landing and CT is measured from initiation of the countermovement until toe-off.4–6 All subjects were familiarized with the procedures during 4 practice trials. Baseline values were calculated as the 4-week average before the first match of the 22 match season. Weekly tests were conducted a minimum of 96 hours and up to 120 hours postmatch, long enough to allow a return to baseline values if athletes followed the expected fatigue-recovery cycle.4 Weekly values were calculated as a percentage of baseline scores.

The Yo-Yo IR2 test was conducted 10 days before the season, using established protocols. It has demonstrated acceptable levels of validity and reliability in elite team-sport athletes.15 The Yo-Yo IR2 requires subjects to run back and forward between 2 points 20 m apart at a progressively increasing predetermined speed in time with an audio signal. Out-and-back 20-m shuttles are separated by 10 seconds of low-intensity activity. Participants abstained from vigorous physical activity for 3 days before the test.

Coaches’ votes were obtained from 5 coaches who ranked each player’s match performance according to their own opinion using the following categories: 1 = poor performance, 2 = moderate performance, 3 = good performance, 4 = very good performance, 5 = excellent performance. Analysis has demonstrated acceptable internal consistency for this measure (Cronbach α = .88–.92).3

Participants’ match exercise intensity was recorded by an accelerometer sampling at 100 Hz, housed inside a global positioning system (GPS) unit (MinimaxX, Team 2.5, Catapult Innovations, Scoresby, Australia). Accelerometer data (LPM from individual x, y, and z vectors) were downloaded postmatch using manufacturer-specific software (Logan Plus v 4.46.0). Accelerometer load has been shown to have high levels of validity and reliability in team-sport-specific movements, and a detailed explanation of the mathematical formula used to calculate this variable has been described previously.13 In addition, HSR meters per minute and meters per minute relative to playing time were simultaneously collected by the same GPS unit collecting accelerometer loadTM-4.3,16,17

Statistical Analysis
LPM values for each match were divided into fatigued and nonfatigued groups based on the 8% CV for FT:CT.3–6 Samples with a score of <92% of baseline (n = 17) were considered fatigued, while the remaining samples (n = 20) were allocated to the nonfatigued group. After log transformation to reduce bias due to nonuniformity of error, the percent difference (± 90% CI) in the relative contribution of individual vectors to total LPM in the fatigued versus nonfatigued state was compared using an Excel spreadsheet.18 This process was repeated with individual adjustment for LPM, HSR meters per minute, meters per minute, Yo-Yo IR2 score and coaches’ votes. A >75% likelihood of the difference exceeding the smallest important value was considered a practically important change.4,5 In cases where the 90% CI interval spanned substantially positive and negative values, the practical outcome was considered unclear.18 In addition, Pearson correlations were calculated between HSR meters per minute, meters per minute, Yo-Yo IR2 score, and coaches’ votes and the relative contribution of each vector in the fatigued and nonfatigued states using SPSS (version 17.0). Individual correlations (± 90% CI) and the magnitude of the difference (± 90% CI), including a qualitative descriptor, between nonfatigued and fatigued values were calculated using an Excel spreadsheet.19 Correlations were considered practically important if there was a >75% chance of the statistic exceeding r = .1.19

**Results**

Baseline mean (± SD) Yo-Yo IR2 scores for the nonfatigued and fatigued groups were 1054 ± 209 m and 998 ± 165 m, respectively (mean difference ± 90% CI = 4.7% ± 10.9%, unclear). The mean percentage (± SD) contributions of the x, y, and z vectors to LPM in the nonfatigued state were 23.5 ± 1.2, 32.4 ± 1.62, and 44.1 ± 2.5, respectively. In fatigue, the percent contributions (± SD) were 23.4 ± 2.7, 34.8 ± 6.9, and 41.9 ± 4.9 for the same vectors. Changes (mean ± 90% CI) in the contribution of individual vectors, including adjustments for LPM,
HSR meters per minute, meters per minute, votes, and Yo-Yo IR2 score, due to fatigue are displayed in Table 1. The largest change was a $-5.8\% \pm 6.1\%$ (86% likely) reduction in the contribution of the $z$ vector to LPM due to fatigue. This degree of reduction in vertical acceleration was maintained (mean 87% likely) when adjusted for a given value of LPM, HSR meters per minute, meters per minute, Yo-Yo IR2 score, and coaches’ votes. When controlling for absolute LPM, the largest reduction due to fatigue occurred in the $z$ vector ($-5.1\% \pm 4.7\%$, 90% likely).

Correlations between the percentage contribution of the $x$, $y$, and $z$ vectors and HSR meters per minute, meters per minute, Yo-Yo IR2 score, and coaches’ votes in the normal and fatigued state are displayed in Table 2. The nonfatigued state revealed numerous practically important correlations. For example, all 3 vectors demonstrated a meaningful relationship to meters per minute (mean 92% likely), while coaches’ votes were unrelated to any other variable. In the fatigued state, only the percent $x$ axis, percent $y$ axis, and HSR meters per minute maintained practically important relationships.

Table 1 Percent Change ± 90% CI and Qualitative Descriptor in Contribution of Individual $x$ (Mediolateral), $y$ (Anteroposterior), and $z$ (Vertical) Vectors to Total Load per Minute Due to Neuromuscular Fatigue and When Adjusted Individually for HSR Meters per Minute, Meters per Minute, Coaches’ Votes, and Yo-Yo IR2 Score

<table>
<thead>
<tr>
<th>% Contribution of individual vector</th>
<th>% Change due to fatigue</th>
<th>Adjusted % Change Due to Fatigue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load/min</td>
<td>HSR m/min</td>
<td>m/min</td>
</tr>
<tr>
<td>$x$</td>
<td>$-0.8 \pm 5.5$, unclear</td>
<td>$-0.4 \pm 5.6$, unclear</td>
</tr>
<tr>
<td>$y$</td>
<td>$5.8 \pm 7.8$, 75% likely ↑</td>
<td>$4.9 \pm 6.2$, unclear</td>
</tr>
<tr>
<td>$z$</td>
<td>$-5.8 \pm 6.1$, 86% likely ↓</td>
<td>$-5.1 \pm 4.7$, 90% likely ↓</td>
</tr>
</tbody>
</table>

Abbreviations: HSR, high-speed running; IR2, Intermittent Recovery Test level 2. Difference in means with a >75% likelihood of exceeding the smallest important value were considered practically important ($\uparrow$ increase, $\downarrow$ decrease). Changes were classified as unclear when the 90% CI overlapped substantially positive and negative values.

Table 2 Correlations (± 90% CI) Between % Contribution of $x$ (Mediolateral), $y$ (Anteroposterior), and $z$ (Vertical) Vectors and HSR Meters per Minute, Meters per Minute, Yo-Yo IR2, and Coaches’ Votes in Nonfatigued and Fatigued States

<table>
<thead>
<tr>
<th>% Vector</th>
<th>Nonfatigued</th>
<th>Fatigued</th>
<th>$\Delta$</th>
<th>% Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSR m/min</td>
<td>$x$</td>
<td>$0.26 \pm 0.39^*$</td>
<td>$-0.28 \pm 0.39$</td>
<td>74%</td>
</tr>
<tr>
<td></td>
<td>$y$</td>
<td>$-0.29 \pm 0.38^*$</td>
<td>$-0.49 \pm 0.52$</td>
<td>86%</td>
</tr>
<tr>
<td></td>
<td>$z$</td>
<td>$0.18 \pm 0.40$</td>
<td>$-0.55 \pm 0.48$</td>
<td>90%</td>
</tr>
<tr>
<td>m/min</td>
<td>$x$</td>
<td>$-0.42 \pm 0.33$</td>
<td>$-0.25 \pm 0.39$</td>
<td>89%</td>
</tr>
<tr>
<td></td>
<td>$y$</td>
<td>$-0.54 \pm 0.43$</td>
<td>$-0.04 \pm 0.41$</td>
<td>91%</td>
</tr>
<tr>
<td></td>
<td>$z$</td>
<td>$-0.57 \pm 0.35$</td>
<td>$-0.09 \pm 0.41$</td>
<td>95%</td>
</tr>
<tr>
<td>Coaches’ votes</td>
<td>$x$</td>
<td>$-0.20 \pm 0.41$</td>
<td>$0.01 \pm 0.41$</td>
<td>61%</td>
</tr>
<tr>
<td></td>
<td>$y$</td>
<td>$0.03 \pm 0.39$</td>
<td>$0.14 \pm 0.37$</td>
<td>52%</td>
</tr>
<tr>
<td></td>
<td>$z$</td>
<td>$-0.19 \pm 0.52$</td>
<td>$-0.01 \pm 0.41$</td>
<td>60%</td>
</tr>
<tr>
<td>Yo–Yo IR2</td>
<td>$x$</td>
<td>$-0.53 \pm 0.32$</td>
<td>$0.16 \pm 0.40$</td>
<td>95%</td>
</tr>
<tr>
<td></td>
<td>$y$</td>
<td>$-0.34 \pm 0.51$</td>
<td>$0.25 \pm 0.36$</td>
<td>75%</td>
</tr>
<tr>
<td></td>
<td>$z$</td>
<td>$-0.46 \pm 0.43$</td>
<td>$-0.03 \pm 0.41$</td>
<td>87%</td>
</tr>
</tbody>
</table>

Abbreviations: HSR, high-speed running; IR2, Intermittent Recovery Test level 2. $\Delta$ represents change in the strength of each correlation between nonfatigued and fatigued states. A >75% likelihood of the magnitude of the difference in the size of $r$ between nonfatigued and fatigued exceeding $r = .1$ was considered practically important.

* $>$75% likelihood of $r > .1$. 

\[ $-0.5 \pm 0.30^*$ \]
**Discussion**

The current results show that NMF status affects how LPM is accrued in elite Australian Football players. In the fatigued state compared with the nonfatigued state, there is a practically important reduction in the contribution of the vertical accelerometer vector to LPM. This reduction remains regardless of covariate, suggesting that NMF modifies the activity profile of elite Australian Football players. Notably, there is a practically important change in the strength of the relationships between HSR meters per minute, meters per minute, and Yo-Yo IR2 and the percentage contribution of individual vectors in the fatigued state.

The reductions in the percentage contribution of the z-vector accelerometer to LPM in the fatigued state may be due to a number of possible mechanisms. Potentially, NMF directly impairs the ability to sprint or accelerate/decelerate, resulting in a greater proportion of LPM being accumulated at the lower end of the HSR meters-per-minute running band. This concept is supported by earlier research that demonstrated a very likely reduction \( r = -.43 \pm .29 \) in the relationship between LPM and HSR meters per minute in the fatigued state.\(^3\) A tendency toward lower speed running would likely result in less vertical acceleration than occurs in higher-speed running or changes of speed.\(^8\) Although not measured in the current study, there is potential for the reduction in the contribution of the z vector to be related to changes in vertical stiffness.\(^9,12\) Reductions in vertical stiffness assessed via changes in the spring-mass model have shown an increase in vertical displacement and ground-contact time.\(^8,9,12\) If a change in ground-contact time accompanied by a disproportionate change in vertical displacement has occurred in the subjects with NMF in this study, the net result could be reduced vertical acceleration due to the combined influence of displacement and time on acceleration. Fatigue-induced modifications in the spring-mass system may occur as a result of the neuromuscular system’s inability to maintain vertical stiffness and manifest as progressively slower running speeds.\(^9\) The reduction in vertical accelerations could reflect players adopting a “Groucho” running pattern, characterized by increased knee flexion, further supporting the notion of less sprinting and a reduced ability to accelerate or decelerate.\(^8\) In addition, players who adopt this running pattern may have an elevated \( O_2 \) cost for a given speed (ie, reduced efficiency) and compound the impact of already inefficient movement.\(^8\) While speculative, it is possible that NMF measured via FT:CT may precede an alteration in vertical stiffness. It is also possible that NMF results in some type of feed-forward-driven modification of movement strategy.\(^20\) Alternatively, there may be an increased perception of effort required to produce high-intensity movements, resulting in decreased output.\(^21\) Given that single maximal sprints between 100 m and 400 m have induced progressive and substantial NMF; performance in elite Australian Football is likely to be hampered by entering a match in an already compromised neuromuscular state.\(^10\)

An interesting finding from the correlation analysis was that only 1 of the 6 \( r \) values likely to be practically important in the nonfatigued state maintained this status in fatigue. The large percent \( x \) versus HSR meters per minute correlation maintained a practically important value in both states. A potentially important change (86% likely) occurred in the percent \( y \) versus HSR meters per minute. It appears that fatigue plays little role in modifying the relationship between lateral movement and HSR meters per minute but results in an inverse relationship between anteroposterior acceleration and this running variable. This provides support for the concept that NMF (either directly or potentially via modifications to vertical stiffness) results in more running at a steady pace or at the lower end of the HSR meters-per-minute band, rather than frequent accelerations and decelerations that characterize the nonfatigued condition.\(^7,9,12\) This would likely result in fewer anteroposterior changes of upper body position (ie, forward and backward lean) during running and therefore a weaker relationship between HSR meters per minute and the percent contribution of the \( y \) vector.

The border-line likely increase in the relative contribution of the \( y \) vector to LPM in the fatigued state coupled with the change in correlation suggests that NMF fatigue results in movements in the anteroposterior plane that are not associated with either total or high-speed running distance.

A novel finding from this research is the inverse correlation between the vertical vector and capacity in the nonfatigued state. This suggests that elite Australian Football players with a high capacity competing in a nonfatigued state have a lower relative contribution to total LPM from vertical accelerations than their fatigued counterparts. This could be because elite Australian Football players with a high capacity not only complete large volumes of lower-speed running that involve less vertical acceleration, and in relative terms this constitutes a larger proportion of total LPM. In the fatigued state, athletes may generally maintain their HSR meters-per-minute profile (although the distribution above 15 km/h may vary, with more at the lower end of this scale) but modify the amount of lower-speed running in an effort to “pace” their output.\(^22\) This would result in a relatively higher contribution of HSR meters per minute and subsequent increase in the impact of vertical acceleration on LPM. Previous work in elite Australian Football has demonstrated a modification to low-speed activity as a result of acute within-match fatigue, and the current research suggests this may also occur as a result of preexisting fatigue.\(^23\) Critically, this practically important inverse relationship is substantially reduced (even when Yo-Yo IR2 score is accounted for) due to fatigue and becomes practically unimportant. Consistent with a previous study, this suggests that the ability of elite Australian Football athletes to use capacity to accumulate LPM diminishes in fatigue.\(^3\) A relative reduction in low-speed activity may have important implications for individual and team performance.
All 3 vectors displayed large practically important relationships to meters per minute and, critically, the z-vector relationship is inverse. It appears that a high proportion of vertical displacement is counterproductive to amassing distance in elite Australian Football players. The primary contributor to meters per minute in the nonfatigued state seems to be relatively constant steady-state running, perhaps at the low end of the HSR band, involving minimal changes in vertical displacement. Total distance can be accumulated with an increased amount of lower-speed running involving less change of pace and therefore less acceleration in the vertical plane. This finding adds support to the concept that a relative reduction in low-speed activity occurs due to NMF in elite Australian Football players. In fatigue, the average likelihood of a practically important change in all 3 vectors is 96% and results in all correlations losing practical importance. Clearly, NMF reduces the importance of individual vectors to meters per minute in elite Australian Football players.

Given previous research, it might be considered unexpected that there is no practically important correlation between the percent contribution of any vector and coaches’ votes. That previous study found a large correlation between LPM and coaches’ votes in the nonfatigued state that was reduced due to fatigue. However, the work examined the relationship between total LPM and performance as measured by coaches’ votes, rather than the influence of individual vectors. The results of the current study suggest that the contribution of isolated vectors to LPM does not directly influence the coaches’ perception of performance in elite Australian Football players. It appears that the combination of changes to the way LPM is accumulated due to fatigue is more important than individual vector modifications. This supports previous work demonstrating that performance in elite Australian Football players is influenced by a combination of factors.

The magnitude of the correlations between Yo-Yo IR2 score and all 3 vectors agrees with previous work and highlights that the importance of capacity to movement in elite Australian Football players depends on fatigue status. Both lateral and vertical acceleration vectors are related to capacity by a large magnitude in the nonfatigued state but not in fatigue. In all cases the change in the strength of the correlations is >75% likely to be of practical value. In the nonfatigued state, elite Australian Football athletes with high capacity appear able to accumulate a large percent of LPM by performing lateral movements. The influence of Yo-Yo IR2 score on this ability is substantially diminished in the fatigued state and, as suggested earlier, may be the result of modifications to vertical stiffness.

**Practical Applications**

This study confirms that NMF affects movement in elite Australian Football players and provides insight into some of the specific activity-profile changes that occur. It also provides further evidence of the value of routine monitoring of LPM with the use of triaxial accelerometers and NMF via FT:CT in elite Australian Football players. Coaches are likely to perceive athletes who play in the presence of NMF to have performed relatively poorly. Given the potential for NMF to modify pacing strategy (via an influence on low-speed running) and subsequently affect team structures, coaches could potentially use the assessment of NMF to assist with team selection. Accelerometers may also have a potential use in real-time elite Australian Football activity-profile monitoring. For example, the collection of sufficient data on individual players may allow the establishment of threshold values for individual accelerometer vectors that may be useful as an indicator of a change in a player’s movement strategy during a match. If team staff are aware that a player has entered the match in a state of NMF, such information could be used to inform interchange rotations or substitutions. Future research should investigate the underlying mechanisms responsible and the movement modifications due to NMF fatigue in more detail and attempt to verify the suggested explanations offered here. This may include analysis of LPM in conjunction with GPS data from units operating at a higher sample rate than those in the current study (eg, 10 Hz), which may enable a more precise determination of changes to running profile (ie, narrow speed bands) associated with NMF. Such research may also include determining whether prematch NMF status modifies within-match fatigue patterns, clarifying the contribution of central and peripheral fatigue factors and examining methods of accelerating recovery from NMF. However, a proportion of LPM in elite Australian Football would likely be accumulated during body contact, and it is unclear how NMF affects this. In addition, although variables such as playing position, scoreline, tactics, opposition, and venue could have influenced the results of this work, it appears unlikely to have had a major influence, as the data represent a number of elite Australian Football players and a spread of matches.

**Conclusion**

This research demonstrates the practically important impact of NMF on movement strategy in elite Australian Football players. Through either the direct influence of NMF or via some other mechanism preceded by NMF, there is a likely practical reduction in the contribution of vertical acceleration to total LPM, even when HSR meters per minute, meters per minute, and Yo-Yo IR2 are taken into account. Fatigue also modifies the strength of a number of the relationships between individual vectors, running measures of activity profile, and capacity. In combination, these results suggest a probable tendency toward more running at the lower end of the high-speed band, less change of speed, and a resultant change in the contribution of specific vectors to LPM in the fatigued state. NMF may also affect low-speed movement as part of a pacing strategy. This finding adds to previous work demonstrating that NMF moderates the relationships between total LPM...
and coaches’ votes in elite Australian Football players.\textsuperscript{3} Fundamentally, fatigue appears to limit the ability to maximize the use of capacity in the accumulation of LPM and to selectively alter the relationship between the percentage contribution of the \(x\) and \(z\) vectors and Yo-Yo IR2 score.

References


