Neuromuscular Fatigue Risk in Elite Footballers: A Longitudinal Survival Analysis

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KEYWORDS: Biomechanics, Countermovement Jump, Cox Regression, Neuromuscular Fatigue, Football.

Introduction

Monitoring neuromuscular fatigue is essential for performance optimisation and injury risk reduction in elite football [1]. The countermovement jump (CMJ) is commonly used due to its sensitivity to neuromuscular function [2]. However, elite athletes may preserve jump height through altered movement strategies, masking fatigue adaptations [1]. CMJ assessments are often conducted irregularly, limiting cross-sectional analyses.

Survival analysis provides a time-dependent approach to quantify fatigue risk while accounting for censored observations and uneven monitoring schedules [3]. This study examined biomechanical predictors of neuromuscular fatigue slumps in professional footballers using a time-varying Cox Proportional Hazards model.

Methods

A total of 146 longitudinal CMJ observations were obtained from professional male and female footballers using dual force platforms (VALD ForceDecks). Force–time data were processed using a validated VALD extraction workflow [4]. Fatigue events were defined as a reduction in Modified Reactive Strength Index (mRSI) of at least 0.8 standard deviations below each athlete's historical baseline [1].

A multivariate Cox Proportional Hazards model with a counting process $[start, stop]$ structure was applied to accommodate irregular testing intervals. Predictors included Jump Height, normalised Concentric Power, Countermovement Depth, Braking Impulse, Age, and Sex. Statistical significance was set at $p < 0.05$, and discrimination was assessed using the concordance index.

All procedures conformed to the Declaration of Helsinki. Data were collected by a collaborating sports performance centre during routine monitoring, with informed consent obtained from all participants. De-identified data were shared under a data-sharing agreement and analysed anonymously.

Results

The model demonstrated good predictive performance (concordance index = 0.805), with acceptable overall fit ($p = 0.033$). Age emerged as a significant predictor of fatigue risk ($p =$

0.026), with each additional year associated with a 24.2% increase in hazard ($HR = 1.24$). Male sex was associated with a lower fatigue hazard ($HR = 0.41$), but was not statistically significant ($p = 0.24$). Full estimates are presented in Table 1.

Table 1: Multivariate Cox Proportional Hazards Model Results ($n = 146$, Events = 12)

Variable	Coef	Exp(coef)	SE	z	p
Jump Height	-0.062	0.940	0.123	-0.504	0.614
Concentric Power	-0.168	0.846	0.155	-1.083	0.279
CM Depth	-0.150	0.861	0.084	-1.773	0.076
Braking Impulse	-0.025	0.975	0.025	-1.025	0.305
Age	0.217	1.242	0.097	2.231	**0.026***
Sex (Male; Female = ref.)	-0.882	0.414	0.754	-1.169	0.242

$^{*}p < 0.05$

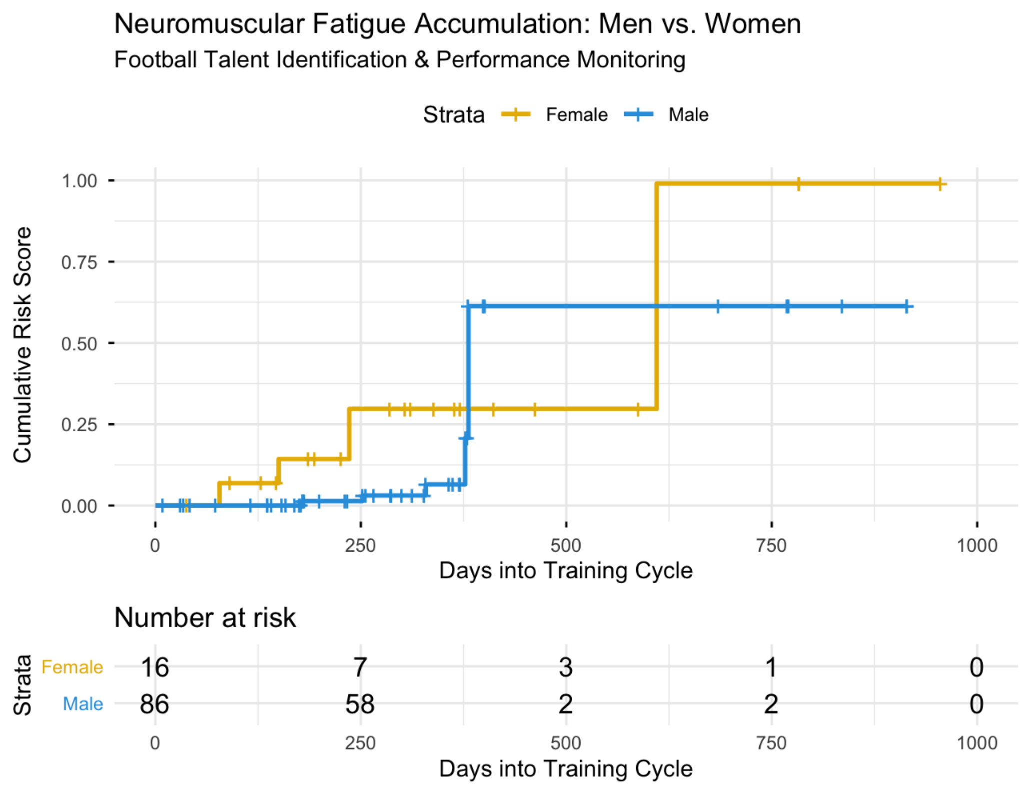

Figure 1: Cumulative hazard of neuromuscular fatigue accumulation in male and female footballers across the training cycle.

Female players showed earlier increases in cumulative hazard compared with males (Figure 1), although sex was not a significant predictor in the adjusted model.

Discussion and Conclusion

Neuromuscular fatigue in elite football is a dynamic, time-dependent process not captured by isolated performance metrics. Strong model concordance indicates that longitudinal biomechanical assessment provides greater insight than jump height alone [2]. The age-related increase in fatigue hazard likely reflects cumulative neuromuscular loading and reduced recovery capacity.

Although sex-specific differences in fatigue timing were observed, these findings should be interpreted cautiously. Overall, time-varying survival analysis offers a practical framework for athlete monitoring and informed load management.

References

[1] Gathercole R, Sporer B, Stellingwerff T, Sleivert G. Alternative countermovement jump analysis to quantify acute neuromuscular fatigue. *Journal of Strength and Conditioning Research*. 2015;29(3):770–778.

[2] Claudino JG, Cronin J, Mezêncio B, et al. The countermovement jump to monitor neuromuscular status: A meta-analysis. *Sports Medicine*. 2017;47(5):987–1002.

[3] Williams S, West S, Cross MJ, Stokes KA. Monitoring the athlete training response: Subjective self-reported measures trump commonly used objective measures. *Sports Medicine*. 2017;47(10):2005–2017.

[4] VALD Performance. *ForceDecks User Guide and Data Extraction Manual*. Brisbane, Australia: VALD Performance Pty Ltd; 2024.