Investigating force-velocity and acceleration-speed profiling in elite football

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I dedicate this thesis to my Mum who always supported me, encouraged me to pursue my academic journey, and forever believed in me. I told you I could do it.

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Declaration

I declare that all the data presented is my own work unless stated otherwise and this thesis was constructed by myself. Appropriate referencing has been used for all the published literature referred to within this thesis. None of the data presented within this thesis has previously been submitted for assessment towards a higher degree.

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1.0 Abstract

1.1 Objectives

Force-velocity profiling is becoming more common in elite football environments, to assess sprint acceleration performance and mitigate hamstring muscle injury (HMI) risk. Acceleration-speed profiling has recently been introduced as an alternative to force-velocity profiling, but there is limited research exploring the interchangeability of the two approaches. It is critical that profiling methods are valid and reliable to assess and monitor elite football players' individual force-velocity or acceleration-speed profiles, to help practitioners orient training and rehabilitation programmes, indicate and mitigate injury risk, and improve sprint acceleration and overall football performance. The aim of the project is to investigate force-velocity and acceleration-speed profiles in elite football, including an examination of the validity and reliability of current profiling devices, to provide insight into elite footballers' sprint mechanical capabilities and anecdotal evidence pertaining to prospective HMI risk within this population.

1.2 Methods

Twenty-nine elite youth football players from the academy of an English Premier League team volunteered to participate (mean ± SD: age 18.04 ± 1.35 years). Study 1 consisted of an initial 40-m maximal sprint testing protocol conducted utilising a combination of the MySprint app and force-velocity profile calculation spreadsheet, alongside global positioning system (GPS) monitoring. This was followed several months later by a 30-m maximal sprint testing protocol, simultaneously measured using the radar device, MySprint app, and GPS. The radar device (Stalker ATS Pro II; Applied Concepts, Plano, TX, USA) measured instantaneous velocity at a sampling rate of 46.875 Hz and was placed on a tripod 10-m behind the athletes. An iPhone XR (Apple Inc., Cupertino, CA, USA) recorded maximal sprints using the built-in standard HD video function (1080p at 60 frames per second), with videos subsequently imported into the MySprint app (Pedro Jiménez-Reyes., 2016, version 2.0.1). Testing protocols were conducted at the start of team training sessions, both corresponding to 4-days prior to match-day (MD-4). Study 2 assessed distance-induced variation in force-velocity profiles derived from GPS data of the 30 and 40-m maximal sprint tests. Study 3 comprised of deriving acceleration-speed profiles in-situ from the GPS data collected during the remainder of the training session after the 30-m maximal sprint testing protocol, and from the competitive game played the following weekend. The training session used for GPS data collection consisted of a medium-sided game lasting 45-minutes (8 vs. 8 + 2 GKs). Study 4 involved post-analysis of acceleration-speed profiles and anecdotal evidence pertaining to prospective HMI risk using quadrant charts. The maximal sprint testing, training session, and competitive game were performed on natural grass open-field and were recorded for each athlete utilising 10-Hz GPS units (APEX Pro, STATSports, Northern Ireland).

1.3 Results

1.3.1 Study 1 – Validity and reliability of force-velocity profiling techniques

There was no significant difference in F_0 or V_{max} when the MySprint analysis procedure was repeated by the same tester for the 30-m maximal sprint testing protocol (for F_0 or V_{max}, $p >$ 0.05, RMSE and CV: 0.19 N/Kg and 2.9%, 0.07 m/s and 0.54%, ICC = 0.832 and ICC = 0.976). There were significant differences in F_0 and V_{max}, when the MySprint app and spreadsheet analysis procedure was repeated by the same tester for the 40-m maximal sprint testing protocol (for F_0 or V_{max}, $p < 0.05$ with medium to large effect sizes, RMSE and CV: 0.61 N/Kg and 3.81%, 0.41 m/s and 2.64%, ICC = 0.871 and ICC = 0.483). There was no significant difference in F_0 or V_{max} ($p > 0.05$, RMSE and CV: 0.08 N/Kg and 0.43%, 0.01 m/s and 0.14%, ICC = 0.995 and ICC = 0.998), and significant very strong associations between F_0 and V_{max} ($p < 0.05$, F_0 rho = 0.964, and V_{max} rho = 0.991), between the MySprint app and the calculation spreadsheet analysis procedures for the 30-m maximal sprint testing protocol. There was no significant difference in F_0 or V_{max} between the two testers performing the MySprint app analysis procedure for the 30-m maximal sprint testing protocol (for F_0 and V_{max}, $p > 0.05$, RMSE and CV: 0.18 N/Kg and 1.04%, 0.06 m/s and 0.42%, ICC = 0.986 and ICC = 0.988. Bland-Altman limits of agreement (±1.96 SD) were ±0.03 N/Kg and ±0.008 m/s, for F_0 and V_{max}). There were significant differences in F_0 and V_{max} between the MySprint app and radar device ($p < 0.05$), but no significant differences in F_0 or V_{max} between the GPS and radar device ($p > 0.05$, Bland-Altman limits of agreement (±1.96 SD) were ±0.194 N/Kg and ±0.09 m/s, for F_0 and V_{max}) from the 30-m maximal sprint testing protocol. There were no significant differences in F_0 or V_{max} between the two sprints performed by each player for all equipment types used (MySprint/Radar/GPS), with similar levels of reliability reported between the GPS and radar device (for F_0 and V_{max} $p > 0.05$, MySprint app (ICC = 0.285 – 0.865, RMSE and CV: 0.72 N/Kg and 3.76%, 0.21 m/s and 1.48%), radar device (ICC = 0.324 – 0.548, RMSE and CV: 1.11 N/Kg and 8.66%, 0.30 m/s and 2.22%), and GPS (ICC = 0.064 – 0.437, RMSE and CV: 1.20 N/Kg and 9.59%, 0.40 m/s and 2.64%). There was increased reliability and level of agreement in V_{max} compared to F_0, within all equipment types between sprint repeats.

1.3.3 Study 2 – Distance-induced variation in force-velocity profiles

There were significant differences in sprint mechanical variables between the two sprint distances (30 and 40-m) (for F_0, V_{max}, and FV_{slope}, $p < 0.05$, with large effect sizes reported: rank biserial correlation = 0.857, 0.786, and 0.893), with the longer sprint distance resulting in reduced F_0 and FV_{slope}, but higher V_{max} when compared to the shorter sprint distance.

1.3.4 Study 3 – Acceleration-speed profiling in-situ

The acceleration-speed profile S_0 was higher in the competitive game compared to training ($p < 0.05$, with medium effect size reported: rank biserial correlation = 0.479), but there were no significant differences in A_0 or AS_{slope} ($p > 0.05$). There were no significant differences in F_0 and A_0, or V_{max} and S_0 ($p > 0.05$) between the 30-m maximal sprint testing protocol (GPS force-velocity profiling) and training session (GPS acceleration-speed profiling in-situ).

1.3.5 Study 4 – Acceleration-speed profiling in-situ and potential prospective HMI risk

During the competitive game there was a shift towards higher S_0 relative to the squad average with A_0 remaining fairly consistent, and more players displayed significant deviation from the squad average for both A_0 and S_0 when compared to the training session.

1.4 Conclusions

Study 1 reported high intra and inter-tester reliability when using the MySprint app to derive force-velocity profiles from 30-m maximal sprint testing and provides the most valid and reliable force-velocity profiling technique (GPS). Study 2 demonstrates that 30-m sprint testing distance should be used for maximal horizontal force and 40-m for maximal running velocity assessment. Study 3 highlights differences in acceleration-speed profiles between training and competitive games, proposing that ~45 minutes of training data (MD-4) is adequate to provide acceleration-speed profiles in-situ which closely resemble force-velocity profiles from maximal sprint testing meaning practitioners can use acceleration-speed profiling in-situ interchangeably with force-velocity profiling. Study 4 elucidates that acceleration-speed profiling in-situ can be used to indicate higher potential prospective hamstring muscle injury risk during competitive games in the elite football environment.

2.0 Introduction

Sprinting actions are a major component of elite football performance (Faude et al., 2012: Haugen et al., 2014), proving integral to beneficial performance outcomes (Ekstrand et al., 2012), incidences of which have been reported to have increased in the English Premier League in recent years (Allen et al., 2024). Identifying and quantifying the main sprint mechanical variables is essential to understand and evaluate sprint acceleration performance (Rabita et al., 2015) and assess hamstring injury risk (Lahti et al., 2020: Edouard et al., 2024). Hamstring muscle injuries (HMI) are the most prevalent form of injury sustained in elite football with an average of 22% of players sustaining at least one HMI per season with nearly one-third of HMIs being reported to recur (Lahti et al., 2020). HMIs in professional football have increased by 4% annually since 2001, with reinjury rates reported to be between 14% and 63% (Shamji et al., 2021), often accompanied by extensive lay-off periods (Ekstrand et al., 2016). The typical pattern of HMI occurrence in professional football is during non-contact or indirect contact such as during sprinting actions which require rapid movements with high eccentric demands of the posterior thigh (Gronwald et al., 2022: Astrella et al., 2024).

The force-velocity profile is commonly used to assess the determinants of sprint kinematics and performance in elite football (Jiménez-Reyes et al., 2018: Baumgart et al., 2019: Haugen et al., 2020), encapsulating the linear relationship between horizontal force and velocity obtained during human movement (Samozino et al., 2016). Studies have associated alterations in force-velocity profiles with retrospective HMI (Mendiguchia et al., 2016: Mendiguchia et al., 2014: Marine et al., 2023) and potential prospective HMI risk (Edouard et al., 2021: Jiménez-Reyes et al., 2022: Edouard et al., 2024). Therefore, it is important to monitor changes in force-velocity profiles to enhance performance and mitigate HMI risk. Force-velocity profiles have historically been analysed and evaluated utilising force platforms or instrumented treadmills which directly measure horizontal antero-posterior and vertical ground reaction force components, alongside horizontal forward velocity, over the entire sprint duration (Morin et al., 2010: Chelly & Denis., 2001). Whilst providing high levels of accuracy, they inhibit natural sprint running technique, are costly, and time-consuming, thus hindering their accessibility and practical use (Morin & Seve., 2011). Previously, several reference methods, namely those measuring displacement (timing photocells) or velocity (radar/laser systems), as a function of time (Haugen & Buchheit., 2016) were almost exclusively used for force-velocity profiling. More recently however, the 'simple method' of determining force-velocity relationships (Samozino et al., 2016) has been implemented, based on indirectly analysing the kinematics and kinetics of the athletes' centre of mass (COM) during sprinting using an inverse dynamic approach (Di Prampero et al., 2005).

This ‘simple method’ has been reported as an accurate, reliable, valid, and precise approach to determining sprint force-velocity profiles in practical field conditions and mitigates against the ‘traditional’ methods’ drawbacks (Samozino et al., 2016: Morin et al., 2019). Smartphone applications such as MySprint, and global positioning systems (GPS) which integrate the ‘simple method’ are being more frequently used for force-velocity profiling due to their enhanced accessibility (Morin., 2017: Cormier et al., 2023b). Intra and inter-tester reliability is critical when performing force-velocity profiling analysis as potential measurement inaccuracies are magnified when determining integrative indexes including theoretical maximal horizontal force (F_0), theoretical maximal running velocity (V_0), maximal running velocity (V_{max}), and the overall orientation of the profile (FV_{slope}) (Samozino et al., 2022a). Consequently, examining the intra-tester reliability provides basis for the current study through adequate reporting of potential sources of error. Assessing the inter-tester reliability provides an indication as to whether different observers can determine force-velocity profiles, with both aspects of reliability proving essential for practitioners working in the elite football environment.

Research has reported validity of the MySprint app (Romero-Franco et al., 2017) and GPS (Clavel et al., 2022) against radar devices. However, these studies assessed validity in isolation against a single ‘gold standard’ reference method, with none incorporating several relevant reference methods simultaneously under the same experimental protocol, emphasising the need to investigate MySprint vs GPS vs Radar device during a maximal sprint testing protocol. Inter-trial reliability of force-velocity profiling techniques has previously been assessed, with research reporting good reliability between sprint repeats (Samozino et al., 2016: Samozino., 2018), though these studies utilised timing photocells to provide split times from which the sprint mechanical variables were derived. Inherent differences in instrument error between the profiling techniques being assessed in the current study (MySprint, GPS, and Radar) and those used in previous studies (timing photocells) will likely induce different magnitudes of variation in sprint mechanical variables between sprint repeats, for the different profiling techniques utilised. The degree to which intra-individual differences contribute to variation in formulated sprint mechanical output variables may differ between equipment types (Samozino et al., 2022a), emphasising the importance of investigating the reliability of the different profiling techniques between sprint repeats. Assessing the validity of the MySprint app and GPS against the ‘gold standard’ radar device simultaneously, and the reliability of different equipment between sprint repeats from maximal sprint testing will highlight the most valid and reliable technique, which can then be implemented by elite football practitioners to measure force-velocity profiles and sprint mechanical variables (Jiménez-Reyes et al., 2022).

Studies have investigated differences in force-velocity profiles between sprint distances, reporting that the optimal force-velocity profile varies due to sprint distance i.e., shorter distance oriented towards the force profile, whereas longer distance orientated towards the velocity profile (Morin et al., 2011: Morin et al., 2012: Slawinski et al., 2017: Haugen et al., 2019: Samozino et al., 2022b). Indirect comparisons and unclear subject specificity within these studies highlights the importance of assessing distance-induced variation in sprint mechanical variables and resultant force-velocity profiles within the same cohort of elite footballers. This could contribute to enhanced research protocols and procedures, and assist practitioners in prescribing targeted testing based on assessing specific profiling aspects.

Force-velocity profiling approaches, including those integrating the ‘simple method’, are still based on a single linear sprint test requiring significant organisation and preparation, which is not representative or specific to football actions that include non-linear accelerations, of various durations and distances, often starting from different initial speeds (Morin et al., 2021). The force-velocity profile can be similarly characterised by the acceleration-speed profile which represents the maximal forward acceleration capability of an individual over the range of their running velocity spectrum, meaning conceptually, the information provided by the acceleration-speed profile closely represents the linear sprint force-velocity profile (Morin et al., 2019; Samozino et al., 2016). Force applied per body mass (N/kg) derived from the MySprint app or GPS data of sprint testing (calculated using the ‘simple method’ (Samozino et al., 2016), is equivalent to acceleration (m/s^2) derived from the GPS in-situ data (calculated using the ‘in-situ method’ (Morin et al., 2021). GPS units have recently been used for acceleration-speed profiling in-situ (Morin et al., 2021: Torres-Ronda et al., 2022), which derives from more contextual data relating to football-specific actions i.e., non-linear sprints starting from different velocities, collected passively during training and competitive games (Caldbeck., 2019: Fitzpatrick et al., 2019: Caldbeck & Dos’ Santos., 2022: Varley & Aughey, 2013: Oliva-Lozano et al., 2020). Imbalances in acceleration-speed profiling in situ variables, alongside deviation in these variables from squad norms potentially contribute to increased HMI risk (Morin et al., 2021: Clavel et al., 2023: Alonso-Callejo et al., 2024). This warrants comparisons to provide basis for force-velocity and acceleration-speed profiling techniques to be used interchangeably to assess athletes’ sprint acceleration performance and potential HMI risk, perhaps contributing to a shift towards non-invasive, accessible and efficient athlete profiling, all of which are vital in the elite football environment.

It is critical that profiling methods are valid and reliable to assess and monitor elite football players' individual force-velocity or acceleration-speed profiles between training and competitive games. This will help practitioners to orient training and rehabilitation programmes, indicate and mitigate injury risk, and improve sprint acceleration and overall football performance (Lahti et al., 2020: Edouard et al., 2021: Morin et al., 2021: Jiménez-Reyes et al., 2022: Clavel et al., 2023). Conducting research within the same cohort of academy players from an English Premier League football club will provide pragmatic contemporary insight for practitioners working within the elite football environment.

2.1 Aim and objectives

The **aim** of the project was to investigate force-velocity and acceleration-speed profiles in elite football, including an examination of the validity and reliability of current profiling techniques, to provide insight into elite footballers' sprint mechanical capabilities and anecdotal evidence pertaining to prospective HMI risk within this population.

Objectives:

- **Study 1** – Validity and reliability of force-velocity profiling techniques:
    - Determine intra and inter-tester reliability when using the MySprint app, or MySprint app and calculation spreadsheet, to derive force-velocity profiles from 30 and 40-m maximal sprint testing protocols.
    - Ascertain the validity of force-velocity profiling techniques (MySprint app and GPS unit) against the 'gold standard' (radar device).
    - Provide the inter-trial reliability of different force-velocity profiling equipment (radar device, MySprint app, and GPS unit).
- **Study 2** – Distance-induced variation in force-velocity profiles:
    - Establish if different maximal sprint testing distances (30 and 40-m) induce variation in force-velocity profiles derived from GPS data.
- **Study 3** – Acceleration-speed profiling in-situ:
    - Examine if acceleration-speed profiles differ between the training session (MD-4) and competitive game.
    - Assess the relationship between 30-m maximal sprint testing (GPS force-velocity profiling) and the training session in-situ (GPS acceleration-speed profiling).
- **Study 4** – Acceleration-speed profiling in-situ and potential prospective HMI risk:
    - Evaluate individuals' potential prospective HMI risk based on acceleration-speed profiles in-situ between the training session and competitive game.

3.0 Literature Review

3.1 Force-velocity profiles encapsulate sprint mechanics in elite football

Maximal sprint performance is determined by an individuals' ability to produce and apply force in the horizontal direction (Morin et al., 2012). Sprint speed, forward acceleration, and power output are key physical determinants of elite football performance (Faude, Koch, & Meyer., 2012), with high-speed running actions proving integral to beneficial performance outcomes (Ekstrand et al., 2012). Identifying and quantifying the main sprint mechanical variables is essential to understand human sprint acceleration performance (Rabita et al., 2015). An integrative macroscopic force-velocity profile incorporates the linear relationship between horizontal force and velocity obtained during sprint performance. The 'simple method' of determining force-velocity relationships (Samozino et al., 2016) is based on analysing the kinematics and kinetics of the athletes' centre of mass (COM) during sprint acceleration using an inverse dynamic approach (Di Prampero et al., 2005). In the initial phase of sprint running, the overall acceleration acting on the athlete's body ($\boldsymbol{g'}$) is the vectorial sum of the forward acceleration ($\boldsymbol{a_f}$) and the earth's acceleration of gravity ($\boldsymbol{g}$):

$$\textbf{Equation 1)}\ \boldsymbol{g'} = \sqrt{\boldsymbol{a_f}^2 + \boldsymbol{g}^2}$$

Both $\boldsymbol{a_f}$ and $\boldsymbol{g}$ are assumed to be applied to the subjects COM, with $\boldsymbol{g'}$ being applied along a line joining the point of contact foot – terrain with the athlete's body COM. The angle '**α**' between the athlete's body ($\boldsymbol{g'}$) and the terrain, which maintains equilibrium, is calculated by:

$$\textbf{Equation 2)}\ \boldsymbol{\alpha} = \arctan \boldsymbol{g}/\,\boldsymbol{a_f}$$

Figure 1 incorporates the constituents and solutions of equations 1 and 2, showing the forces acting upon an athlete accelerating in the forward direction whilst running on flat terrain, with the athlete leaning forward slightly to optimise horizontal force application (Margaria, 1975).

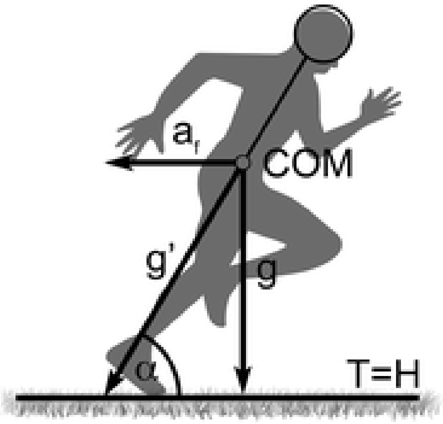

Figure 1: Forces acting on an athlete accelerating forward. The athletes body mass is assumed to be located at the COM: $\mathbf{a_f}$ = forward acceleration, **g** = acceleration of gravity, **g′** = $(\mathbf{a_f}^2 + \boldsymbol{g}^2)^{0.5}$ or resultant acceleration, **T** = terrain, **H** = horizontal, **α** = arctan $\mathbf{g}/\mathbf{a_f}$ or the angle between the athlete's body and T (Adapted from Di Prampero et al., 2015).

The 'simple method' (Samozino et al., 2016), is based on a macroscopic inverse dynamic approach comprising of the following equations which ultimately contribute to the estimation of relevant sprint mechanical properties. Variables are modelled over time, corresponding to step-averaged values.

The horizontal velocity (v_H) – time (t) curve can be computed as follows:

Equation 3) $v_H(t) = v_{Hmax} \cdot (1 - e^{-t/\tau})$

Where v_{Hmax} is the maximal velocity reached and τ the acceleration-time constant. The horizontal position (x_H) and acceleration (a_H) of the body COM as a function of time can be expressed after integration and derivation of $v_H(t)$ over time:

Equation 4) $x_H(t) = \int v_H(t)\, dt = \int v_{Hmax} \cdot \left(1 - e^{-\frac{t}{\tau}}\right) dt$

Equation 5) $x(t) = v_{Hmax} \cdot \left(t + \tau . e^{-\frac{t}{\tau}}\right) - v_{Hmax} \cdot \tau$

Equation 6) $a_H(t) = \frac{dv_H(t)}{dt} = \frac{v_{Hmax} \cdot \left(1 - e^{-\frac{t}{\tau}}\right)}{dt}$

Equation 7) $a_H(t) = \left(\frac{v_{max}}{\tau}\right) \cdot e^{-\frac{t}{\tau}}$

The net horizontal antero-posterior ground reaction force (GRF) (F_H) applied to the body can be modelled over time:

Equation 8) $F_H(t) = m \cdot a_H(t) + F_{aero}(t)$

Where m is body mass (kg) and F_{aero} is aerodynamic drag – proportional to the square of the velocity of air relative to the athlete:

Equation 9) $F_{aero}(t) = k \cdot (v_H(t) - v_w)^2$

Where v_w is the wind velocity and k is the aerodynamic friction coefficient – estimated from the values of air density (ρ, in kg/m^3), frontal area of the athlete (Af, in m^2), and drag coefficient ($Cd = 0.9$)(Van Ingen Schenau et al., 1991):

Equation 10) $k = 0.5 \cdot \rho \cdot Af \cdot Cd$

With:

Equation 11) $\rho = \rho_0 \cdot \frac{Pb}{760} \cdot \frac{273}{273 + T°}$

Equation 12) $Af = (0.2025 \cdot h^{0.725} \cdot m^{0.425}) \cdot 0.266$

Where ρ_0 = 1.293 kg/m is the ρ at 760 Torr and 273 °K, Pb is the barometric pressure (Torr), $T°$ is the air temperature (°C), and h is the athlete's stature (m). Split times are used to determine v_{Hmax} and τ using equation 5. From these two parameters, $v_H(t)$ and $a_H(t)$ can be modelled using equations 3 and 7, respectively. From $a_H(t)$, $F_H(t)$ was modelled over time using equation 8, and $F_{aero}(t)$ could be estimated from equations 9 to 12. For individual computations of k, both the athlete's body mass and height should be measured on the day, prior to sprint testing, alongside recording barometric pressure (Pb), and air temperature ($T°$).

F_H and v_H values can then be calculated using least-square linear and second-order polynomial regressions (Morin et al., 2010: Morin et al., 2012). Force-velocity relationships could then be extrapolated to obtain F_0 and V_0 as the intercepts of the curve with the force and velocity axis, respectively. The above-described biomechanical model makes it possible to estimate GRFs in the sagittal plane of motion during one single sprint running acceleration from simple inputs, ultimately providing force and power-velocity relationships alongside associated sprint mechanical output variables. Figure 2 shows the changes in force, velocity, and power (power-force-velocity profile) for a typical subject performing a 30-m maximal sprint, providing visual representation of the sprint mechanical variables output from the 'simple method' outlined in the above sections (Samozino et al., 2016).

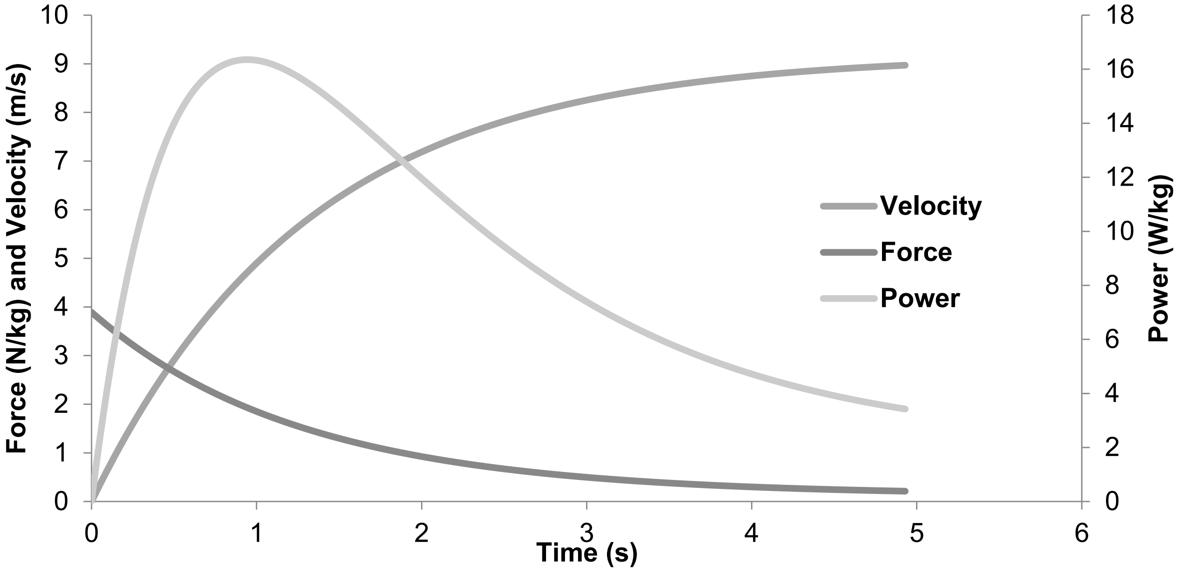

Figure 2: Changes in horizontal force, velocity, and power output over a 30-m maximal sprint for a typical subject (Morin & Samozino., 2019)

Force-velocity profiles provide the specific behaviour of the entire neuromuscular system of the lower extremity during sprinting, giving a more representative reflection of the athlete's ability to develop horizontal force during sprinting tasks (Edouard et al., 2021). The hamstrings play a significant role in horizontal GRF production, regulating overall sprint acceleration performance (Morin et al., 2015). Training interventions designed to enhance horizontal force (F_0) and velocity (V_0) have demonstrated significant correlations with improved sprint acceleration performance (Baena-Raya et al., 2022). Assessing the sprint horizontal force-velocity profile, grouping individual athletes by their specific profile imbalances, and prescribing relevant training interventions designed to attenuate these can improve sprint acceleration performance (Morin & Samozino., 2016: Hicks et al., 2022: Samozino et al., 2022b). These holistic profiling techniques provide insight into the sprint mechanical capabilities of individual athletes and teams as a whole, helping to orient training and rehabilitation programmes, indicate and mitigate injury risk, and improve sprint acceleration performance, within elite football contexts (Edouard et al., 2021: Jiménez-Reyes et al., 2022).

3.2 Critically analysing the ‘simple method’ of sprint force-velocity profiling

Sprint mechanical output variables obtained from force-velocity profiling provide insight into the lower limb neuromuscular system’s behaviour during sprint acceleration (Cormie et al., 2011). These properties originate from a complex integration of different mechanisms, ultimately resulting in total external force production during one or several consecutive limb extensions (Samozino et al., 2016). These mechanisms are dependent upon an individuals’ segmental dynamics, morphology, neurology, and muscle mechanical properties, with all factors assuming the inverse dynamic relationship between force and velocity (Cormie et al., 2010: Bobbert., 2012). It has been questioned if this relationship observed in isolated muscle fibres propagates into locomotion during maximal sprint acceleration, due to the complexity of human movement (Godfrey et al., 2008). This method has been interpreted to purport that the theoretical maximal horizontal force production (F_0) or running velocity (V_0) can be exchanged to alter the overall orientation of the profile (FV_{slope}), which has been critiqued as the respective parameters are physiologically independent of each other (Ettema., 2023). This interpretation can be challenged by acknowledging that these parameters are instead independently modifiable to then modulate the subsequent FV_{slope} (Samozino et al., 2022b).

The ‘simple method’ of determining force-velocity relationships (Samozino et al., 2016) is based on several main assumptions:

1) Overall mass of the athlete is assumed to be at the COM of the body meaning the effects of the motion of the limbs in relation to the COM on the energetics of running are neglected (Di Prampero et al., 2005).
2) There is quasi-null vertical acceleration of the COM over the acceleration phase of the sprint (Samozino et al., 2016).
3) Horizontal aerodynamic drag is merely estimated from stature, body mass, and the fixed drag coefficient (Arsac & Locatelli., 2002).

The ‘simple method’ used step-averaged values (contact and flight time) as opposed to support phase-averaged values (contact time), more closely reflecting the mechanics of the overall sprint acceleration as components acting in the frontal plane are integrated (Di Prampero et al., 2015). This model incorporates large oscillations in instantaneous acceleration as during the flight phase the only horizontal force acting on the centre of mass of the athlete is air resistance meaning acceleration is negative, and, during ground contact, the acceleration is negative during the braking phase before becoming positive during the propulsive phase (Novacheck., 1998). Force output is highly non-linear and discontinuous, with frequent positive-negative oscillations, whereas the model provides a smooth positive curve. During the flight phase, the athlete’s external force application is zero, again questioning the relevance of step-averaged values (Dugan & Bhat., 2005). This mismatching between the modelled acceleration and force, and the actual acceleration and force, potentially influences the method's accuracy and practical application (Cleather et al., 2021). Body type characteristics including stature and mass are integral to the 'simple method' equations, with shorter players often displaying higher initial horizontal force than taller players, purely based on inherent individual anthropometric differences (Weyand., 2022). This could lead to unreliable force-velocity profiles where individual players appear imbalanced in a certain direction whilst contrary to the true situation, potentially leading to false indications (Samozino et al., 2022b). These simplifying assumptions and estimates can be attributed to the indirect nature of this profiling type, leading on to the benefits of this 'simple method' and the evolution of sprint mechanical output profiling techniques from 'traditional' methods.

3.3 Evolution of profiling techniques

3.3.1 Reference methods, reliability, and error consideration

Sprinting performance has previously been analysed and evaluated utilising several 'gold standard' reference methods, namely those measuring displacement (timing photocells) or velocity (radar/laser systems), as a function of time (Haugen & Buchheit., 2016). The biomechanical determinants of sprint performance have generally been assessed using force platforms or instrumented treadmills (Morin et al., 2010). These methods require the measurement of horizontal antero-posterior and vertical GRF components, alongside horizontal forward velocity, over the entire sprint acceleration (Chelly & Denis., 2001). This necessitates the use of specific instrumented treadmills which provide high levels of accuracy but inhibit natural overground sprint running technique (Morin & Seve., 2011), are costly, and time-consuming, thus hindering the accessibility and practical use for most. The 'simple method' previously outlined is an accurate, reliable, valid, and precise approach to determining sprint force-velocity profiles in practical field conditions and mitigates against the 'traditional' methods' drawbacks (Samozino et al., 2016: Morin et al., 2019). Continuing this accessibility and practical implementation trend, smartphone applications such as MySprint which integrate the 'simple method' are being more frequently used for force-velocity profiling (Morin., 2017).

Studies utilising sprint force-velocity profiling have demonstrated the importance of intra-tester reliability, standardisation, and familiarisation to ensure adequate methodological rigor through consideration of potential sources of error. The heterogeneity of the population including age, sex, and playing level influence this profiling type meaning continuity in these factors between different studies is required to enable relevant comparisons (Edouard et al., 2021). Ensuring standardisation in the sprint testing protocol regarding specific warm-up procedure (Mendiguchia et al., 2016) and consistency of sprint starts (Mendiguchia et al., 2014) within and between players improves reliability and validity of relevant protocols. This is particularly notable when determining integrative indexes i.e., sprint mechanical outputs of the neuromuscular system estimated from sprint split times, as the potential measurement inaccuracies are magnified in force-velocity profiling (Samozino et al., 2022a). Critical examination and reporting of all potential sources of error will help to illustrate and distinguish the reliability of the underlying force-velocity concept, specific profiling methodology, and input data measurement. Previous studies investigating the reliability of jump (vertical) force-velocity profiling incorporated the mixing of constrained and unconstrained movements within the same testing (Kotani et al., 2022), lacked participant familiarity (Valenzuela et al., 2021), used large and potentially fatiguing testing volumes, inconsistent starting positions, and variable test-retest jump height (Lindberg et al., 2021). These imprecise testing procedures and biological variation are likely to cause divergence in input data, subsequently influencing relevant reliability measures and perhaps leading to the conclusions that these jump force-velocity profiling techniques were unreliable (Table 1). The underlying physiological, neuromuscular, and biomechanical constituents of vertical force-velocity profiles derived from jump testing involve a complex and intricate interplay between mechanical output variables, similar to horizontal force-velocity profiles derived from sprint testing meaning the reliability concepts outlined above can be applied interchangeably.

Table 1 Methodology and output variable reliability of previous jump force-velocity profiling studies. Testing procedures/limitations likely caused divergence in input data thus altering jump force-velocity variable outputs and associated reliability measures.

Study	**Methodology/*Limitation***	**Output Variable Reliability**	**Interpretation**
Kotani et al., 2022	Between-session reliability of squat jump force-velocity profiling. ***Mixed constrained and unconstrained movements within same testing***.	Coefficient of variation = 24.5% Intraclass correlation coefficient = 0.48	High variation and low ICC values indicate unreliable in the measurement of squat jump derived force-velocity output variables.
Valenzuela et al., 2021	Analyse differences in force-velocity profiles derived from constrained and unconstrained vertical jumps. ***Subjects not familiar with vertical jump procedures (between constrained Smith Machine and unconstrained free weights)***.	Coefficient of variation = 6.65% (F_0), 23.55% (V_0), and 27.1% (FV_{slope}). Intraclass correlation coefficient = 0.495 (F_0), 0.42 (V_0), and 0.27 (FV_{slope}).	High variation and low ICC values indicate unreliable in the measurement of vertical jump derived force-velocity output variables (F_0, V_0, and FV_{slope}).
Lindberg et al., 2021	Examine the test-retest reliability and agreement across methods for assessing individual force-velocity profiles. ***Fatigue inducing testing volume (incremental loading) and variable test-retest jump height***.	Coefficient of variation = 8% (F_0), 16% (V_0), and 25% (FV_{slope}). Intraclass correlation coefficient = 0.805 (F_0), 0.445 (V_0), and 0.495 (FV_{slope}).	High variation and low ICC values (besides ICC showing good agreement in F_0) indicate unreliable in the measurement of squat and countermovement jump derived output variables (F_0, V_0, FV_{slope}).

3.3.2 MySprint app force-velocity profiling

When conducting anaerobic performance testing amongst the elite male footballer population maximal sprinting velocity peaks between 20 – 40-m, at 8.8 – 9.0 m/s (Haugen et al., 2013), suggesting that force-velocity profiling protocols should be conducted over distances of around 40-m to facilitate maximal performance and provide the most reliable and valid sprint mechanical output variables and resultant sprint force-velocity profiles (Buchheit et al., 2012). The original MySprint app was developed to determine sprint mechanical output variables or resultant force-velocity profiles from 40-m maximal sprints, and has been validated against the 'gold standard' radar device, with negligible differences in sprint split time calculation between two independent observers indicating high inter-tester reliability (Romero-Franco et al., 2017). However, the current version of the MySprint app (version 2.0.1) is based on analysing the sprint mechanical output variables or resultant force-velocity profiles from 30-m maximal sprints. Consequently, a combination of the MySprint app to calculate split times then inputting these into a force-velocity profile calculation spreadsheet (Morin & Samozino., 2019) is now required to provide relevant output data for 30-m maximal sprints. Therefore, the tester must be capable of using the combination of the MySprint app to reliably generate sprint split times, and the force-velocity calculation spreadsheet to derive resultant sprint mechanical output variables, hence the intra-tester and inter-testing method reliability studies.

Inter-tester reliability is relevant in elite football environments as multiple observers are often required to collect and assess large amounts of data, over multiple testing days, perhaps overseen by different staff members. No study has demonstrated the intra or inter-tester reliability of 40-m sprint split time and sprint mechanical output variable calculation using the latest MySprint app (version 2.0.1) and calculation spreadsheet. Few studies have investigated intra-tester reliability of the current MySprint app for sprint split time calculation and thus resultant mechanical variable computation from 30-m maximal sprint testing, finding good-to-excellent levels of agreement (ICC = 0.862 – 0.984) (Mildenberger et al., 2024), alongside low dispersion of measurements (CV = 1.307%), reporting high test-retest reliability (Thapa et al., 2023). However, both studies accounted for parallax error differently, placing vertical marker poles at different distances to the current study as the perpendicular distance of the camera was 18-m as opposed to 10-m away from the sprint distance midpoint (15-m) (Stenroth et al., 2023), likely modulating sprint split time and resultant mechanical variable calculations. The current MySprint app designed for 30-m maximal sprint analysis suggests 10-m (Jiménez-Reyes., 2016), whereas the original app designed for 40-m maximal sprint analysis recommended 18-m perpendicular distance of the camera from the sprint distance midpoint (Romero-Franco et al., 2017). The latter study recruited 'physically active university students' (Thapa et al., 2023), likely preventing application to the elite footballer population.

The MySprint app uses two-dimensional (2D) video analysis meaning the accuracy, validity, and reliability of the calculated sprint mechanical outputs are restricted by digitisation of data, image quality, and speed of capture, as slower frame rates induce sampling rate error (Bartlett & Payton., 2008). The 'gold standard' for kinematic running analysis has long been three-dimensional (3D) motion capture. These systems incur significant spatial, temporal, and financial costs, as with the force platforms and instrumented treadmills mentioned previously, emphasising the requirement for accessible alternatives (McLean et al., 2005). 2D video analysis provides a more feasible option for evaluating kinematics but is limited by the degree to which it can capture the dynamic and complex multiple planar motions which occur during maximal sprint acceleration performance (Munro et al., 2012). The 'simple method' utilised by the MySprint app only examines forces developed in the sagittal plane whereas 3D systems capture sagittal, coronal, and transverse plane movement (Richards et al., 2022). Incorporating triaxial application of force in the vertical, anterior-posterior, and medio-lateral directions more closely represents force production and provides a more detailed analysis of movement during maximal sprint acceleration (Maykut et al., 2015). Despite the drawbacks several studies have utilised 2D motion capture systems including the MySprint app, to validate and investigate force-velocity profiling in relation to training interventions, performance, and injury, thereby promoting the implementation of these methods to assess frontal plane kinematic variables during sprint acceleration in these contexts (Romero-Franco et al., 2017: Bettariga et al., 2023: Mendiguchia et al., 2016: Maykut et al., 2015).

3.3.3 GPS acceleration-speed profiling in-situ

Global positioning systems (GPS) (Morin et al., 2021), and light detection and ranging (LiDAR) technology such as Sportlight® (Oxford, UK) (Bampouras & Thomas., 2022) have recently been utilised for athlete tracking and acceleration-speed profiling (Torres-Ronda et al., 2022). Therefore, it is important to distinguish between force-velocity and acceleration-speed profiling techniques if they are to be used interchangeably as the sprint mechanical variable outputs may appear to be comparable but differ slightly in their underlying calculations (Arsac & Locatelli., 2002). The force-velocity profile can be similarly characterised by the acceleration-speed profile which represents the maximal forward acceleration capability of an individual over the range of their running velocity spectrum, meaning conceptually, the information provided by the acceleration-speed profile closely represents the linear sprint force-velocity profile (Morin et al., 2019; Samozino et al., 2016). Disregarding conceptual similarity, slight differences in calculation methods between the two profiling techniques may influence sprint mechanical output variable determination thus potentially inducing alterations in relevant profiles. Adequate levels of agreement have been reported between GPS force-velocity (F_0

and V_0) and acceleration-speed (A_0 – theoretical maximal acceleration, and S_0 – theoretical maximal running velocity) profiling techniques in the measurement of F_0 or A_0 (ICC = 0.48 – 0.90), and V_0 or S_0 (ICC = 0.80 – 0.97) deriving from 40-m maximal sprint testing protocols (Cormier et al., 2023b). The same variables were consistent between 30-m maximal sprint testing (force-velocity profiling: F_0 and V_0) and in-situ monitoring of a training session (acceleration-speed profiling: A_0 and S_0). F_0 or A_0 (strong correlation, r = 0.65), and V_0 or S_0 (strong correlation, r = 0.56) (Komino., 2022). Inter and intra-athlete comparisons can be conducted using force-velocity and acceleration-speed profiling interchangeably (Alonso-Callejo et al., 2024). This is supported by fundamental biomechanical principles as shown in equations 13 and 14 which demonstrate how force applied per body mass (N/kg) derived from the MySprint app or GPS data of maximal sprint testing (calculated using the 'simple method' (Samozino et al., 2016), is equivalent to acceleration (m/s^2) derived from the GPS in-situ data (calculated using the 'in-situ method' (Morin et al., 2021).

Equation 13) $F = m \cdot a$

Equation 14) $a = \frac{F}{m}$

Where F (N = kg x m/s^2) becomes a (m/s^2 = N/kg).

3.4 Distance-induced variations in force-velocity profiles (30-m vs 40-m)

Sprint acceleration performance is dependent upon the force-velocity profile, encapsulating the ratio between horizontal force production capacities at low and high velocities i.e., slope of the force-velocity relationship (Samozino et al., 2022b). This study reported the optimal force-velocity profile varied due to sprint distance i.e., shorter distance (5 – 15-m) orientated more towards the force profile, whereas longer distance (>15-m) orientated more towards the velocity profile. For sprint acceleration up to 30-m, performance was largely explained by maximal power output and to a lesser extent by the degree to which the force-velocity profile deviated from the optimal profile. For shorter (<10-m) or longer (>20-m) sprint accelerations, the contribution of this phenomena to performance increases, with optimal force-velocity profiles oriented toward force or velocity capabilities, respectively. Stronger correlations have been identified between sprint performance and FV_{slope} with increasing sprint distance, sprint performance and F_0 with shorter sprint distance, and sprint performance and V_0 with increasing sprint distance (Haugen et al., 2019), supporting the findings of Samozino et al., (2022b). This delineates previous studies investigating longer sprint acceleration distances (40 – 100-m) which found sprint acceleration performance to mainly rely upon maximal power output and velocity capabilities (Morin et al., 2011: Morin et al., 2012: Slawinski et al., 2017). These studies focused on sprint distances from 5 to 40-m, but did not directly compare relevant sprint mechanical variables between 30 and 40-m sprint accelerations, subject specificity is unclear i.e., level of soccer player unknown, and inter-individual biological differences were not accounted for as different samples of athletes were used between sprint distances. This demonstrates the need for research investigating differences in force-velocity profiles between 30 and 40-m sprint accelerations, within the same cohort of elite footballers.

3.5 Validity and reliability of force-velocity and acceleration-speed profiling

The relevant force-velocity profiling techniques (MySprint app and GPS unit) require validation against the ‘gold standard’ radar device so they can be used interchangeably to assess athletes’ sprint acceleration performance in different contexts where the type of primary data collection equipment needed is scenario dependent i.e., training session vs competitive game. When determining force-velocity profiles, GPS is valid and reliable against radar devices (Clavel et al., 2022), and MySprint is valid against radar devices and timing photocells (Romero-Franco et al., 2017). The intraclass correlation coefficient (ICC) has been used to report the excellent reliability (level of agreement) between different force-velocity profiling techniques (ICC = 0.979 – 1, for all sprint mechanical variables) (Romero-Franco et al., 2017) and can also be utilised for test-retest, intra-tester, and inter-tester reliability analyses (Koo & Li., 2016). The root mean square error (RMSE) was used to validate a player tracking system in the measurement of velocity and acceleration during football-specific tasks, displaying low values for velocity RMSE (0.08 – 0.12 m/s) but slightly higher values for acceleration RMSE (0.36 – 0.6 m/s^2) (Bampouras & Thomas., 2022). RMSE can therefore be applied to predict the accuracy and subsequent validity of force-velocity and acceleration-speed profiling models (Romero-Franco et al., 2017). Bland-Altman plots have been utilised to visually display the differences (level of agreement) in computed force-velocity variables between several systems, directly applying to comparisons in this study (Fornasier-Santos et al., 2022). Each of these studies assessed reliability or validity in isolation against a single ‘gold standard’ reference technique, with none incorporating several relevant reference techniques simultaneously under the same experimental protocol, emphasising the need to investigate MySprint vs GPS vs Radar device during a maximal sprint testing protocol.

3.5.1 Reliability of force-velocity profiling techniques

The ‘simple method’ of determining force-velocity relationships incorporated into the MySprint app, GPS, and Radar profiling techniques displays low coefficient of variation (CV) values for intra and inter-individual comparisons of sprint mechanical output variables (0.25 – 6.76%) (Samozino et al., 2016). Profiling techniques based on this ‘simple method’ can reliably detect meaningful changes, and due to the limited variation of such techniques, any change in relevant sprint mechanical output variables and subsequent performance are more likely due to intra or inter-individual differences as opposed to error (Samozino., 2018). These studies utilised timing photocells to provide split times from which the sprint mechanical output variables were derived, ultimately contributing to the individuals' force-velocity profile. Inherent differences in instrument error between the profiling techniques being assessed in the comparison study (Radar device, MySprint app, and GPS unit) will likely induce alterations in CV values between the different techniques. Studies have reported changes in sprint mechanical output variables for the same athlete between repeated trials enacted on the same day (Hermosilla-Palma et al., 2022) and trials conducted throughout the season (Jiménez-Reyes et al., 2022). This reiterates differences in relevant variables and force-velocity profiles either because of intra-individual differences or error, with the magnitude of error varying between profiling techniques due to their implicit constraints. This emphasises the importance of investigating the reliability of the different profiling techniques between sprint repeats as the degree to which intra-individual differences contribute to variation in formulated sprint mechanical output variables may differ between equipment types (Samozino et al., 2022a).

3.5.2 Ecological validity of force-velocity profiling and acceleration-speed profiling in-situ

Force-velocity profiling deriving from single linear sprint testing i.e., using the MySprint app, informs on players' acceleration capacities at different velocities but is not specific to football sprinting actions which are rarely linear due to the relationship between external stimuli and perception-action (P-A) coupling (Caldbeck., 2019). P-A coupling refers to the constant exchange of information between the environment and the selected movement responses to ultimately elicit task completion (Seifert & Davids., 2017). Affordances, defined as potential opportunities for action, underpin the relationship between decision making and the action performed (Myszka., 2018). These affordances are mediated by the nature of the task itself, the individual's own characteristics, and the performance environment (Fajen et al., 2008), with this interplay ultimately determining the type of sprinting occurring during a training session or competitive game. Furthermore, when utilising force-velocity profiling researchers should consider the absence of adequate competitive stimuli which, during match-play, act to stimulate maximal performance in sprinting tasks (Caldbeck, 2019). Competitive elements can be incorporated into the protocol i.e., timing gates, to provide instantaneous feedback and competition between participants which may stimulate performance closer to maximal levels. This is particularly relevant to elite footballers who often possess psychological characteristics contributing to enhanced competitiveness, thus insinuating its importance as a trait to target when seeking maximal performance in tasks such as sprinting (MacNamara et al., 2010).

Acceleration-speed profiling in-situ deriving from more contextual data relating to football-specific situations and actions can be collected passively during play i.e., using GPS units or the Sportlight® system (Oxford, UK) (Morin et al., 2021). The incorporation of football specific contextuality through in-situ monitoring which records sprints of all varieties i.e., linear and curved sprints, means this profiling technique more closely represents football-specific actions as sprinting during football match-play is very rarely linear (Fitzpatrick et al., 2019: Caldbeck & Dos' Santos., 2022). Curved and linear sprints have recently been classified as distinct motor tasks meaning they should be independently assessed, thus supporting the proposed experimental design which incorporates both isolated and in-situ profiling techniques (Fílter et al., 2020). Players usually spend around 30% of time executing game-related activities moving in arced, backward, lateral, and diagonal directions, emphasising the non-linear nature of football-specific actions (Bloomfield et al., 2007). Around 85% of the actions performed at maximum velocity in professional soccer are curvilinear sprints (Filter et al., 2020), further emphasising the importance of non-linear sprint ability as a critical skill for elite soccer players and key determinant of elite football performance outcomes (De Araújo et al., 2018).

Around 98% of maximal acceleration efforts during competitive games start from low to moderate velocities, thus acceleration-speed profiling in-situ better encapsulates football-specific actions when compared to force-velocity profiling starting from a standstill (Varley & Aughey, 2013: Oliva-Lozano et al., 2020). The possible reliability issues with GPS units may elicit obstacles to using the acceleration-speed profiling in-situ method as these problems are accentuated by the cut-off speeds (Scott et al., 2016: Buchheit et al., 2014), non-linear nature of sprints (Pino-Ortega et al., 2022), and maximal acceleration or high-velocity running (Aughey., 2011) that this profiling technique incorporates. The reader is directed towards section 3.7 for extensive evaluation of inherent GPS reliability concerns and rationale as to why GPS profiling was implemented in the current study, alongside further explanation of contextual factors which contribute to altered sprint mechanical output variables and subsequent force-velocity or acceleration-speed profiles. Improving ecological validity through the inclusion of more contextual data is likely to induce higher variation in relevant sprint mechanical variables and resultant force-velocity or acceleration-speed profiles between different training sessions and competitive games due to the influence of a multitude of contextual factors, questioning the minimum amount of data required for profile determination.

3.6 Justification of relevant sprint mechanical output variables

Force-velocity profiling methods provide a multitude of sprint mechanical output variables, but the focus will be on the following: F_0 (N/kg), V_0 (m/s), V_{max} (m/s), and FV_{slope} (see Table 2), as these are the primary contributors to horizontal force production capacity and best encapsulate the overall horizontal force-velocity profile (Morin & Samozino., 2019), proving highly relevant in both performance and injury contexts (Morin & Samozino., 2016: Lahti et al., 2020: Edouard et al., 2021: Jiménez-Reyes et al., 2022). Therefore, assessing these particular variables will likely facilitate comparison between this study and other literature in relevant areas. Acceleration-speed profiling methods provide several sprint mechanical output variables i.e., A_0 (m/s^2) and S_0 (m/s) (see Table 3), which correspond to the force-velocity profiling variables of F_0 (N/kg) and V_0 (m/s), respectively. Equations 13 and 14 (section 3.3.3) detail how the variables obtained from different profiling techniques are equivalent and can be standardised thus enabling comparison of relevant data between force-velocity and acceleration-speed profiling methods (Samozino et al., 2016: Morin et al., 2019: Komino., 2022). This is of particular importance when examining for potential differences in sprint mechanical output variables between training and competitive games, or any situation where different profiling techniques (force-velocity and acceleration-speed based) might be utilised interchangeably to provide relevant data. Tables 2 and 3 provide definitions, practical interpretation, and normative values for the main variables associated with force-velocity and acceleration-speed profiling in sprinting which have been outlined in the above section.

Table 2 Definition, practical interpretation, and normative values of the main variables when using force-velocity profiling in sprinting (Adapted from Morin & Samozino., 2016).

Variable	**Definition**	**Interpretation**	**Normative Values**
F_0 (N/kg)	Theoretical maximal horizontal force production (per unit body mass)	Maximal force output in the horizontal direction corresponding to initial push-off. Higher value = higher sprint specific horizontal force production.	**6.66 – 9.0 N/kg** Elite male footballers (Jiménez-Reyes et al., 2018: Haugen et al., 2020)
V_0 (m/s)	Theoretical maximal running velocity	Maximal sprint-running velocity the athlete would reach if mechanical resistances against movement are null. Also represents capability to produce horizontal force at very high running velocities.	**8.64 – 9.86 m/s** Elite male footballers (Jiménez-Reyes et al., 2018: Haugen et al., 2020)
V_{max} (m/s)	Maximal running velocity	Maximal running velocity in the horizontal direction during sprinting.	**8.91 ± 0.23 m/s** Elite male footballers (Baumgart et al., 2018)
FV_{slope}	Overall orientation of the FV profile Computed as: $FV_{slope} = - F_0 / V_0$	Provides an understanding of the relationship between F_0 and V_0 over the entire sprint acceleration distance.	N/A

Table 3 Definition, practical interpretation, and normative values of the main variables when using acceleration-speed profiling in-situ (Adapted from Morin et al., 2021: Clavel et al., 2023: Komino., 2022). Acceleration-speed variables vary due to contextual (cumulated vs isolated and training vs match data etc.) and technical factors (specific GPS unit worn etc.), thus warranting caution when comparing the range of values reported between studies.

Variable	Definition	Interpretation	Normative Values
A_0 (m/s^2)	Theoretical maximal acceleration	Maximal sprint-acceleration capacity. Higher value = higher sprint specific acceleration. Equivalent to F_0 (N/kg).	**5.14 – 9.22 m/s^2** Elite male footballers (Morin et al., 2021: Alonso-Callejo et al., 2022: López-Sagarra et al., 2022: Clavel et al., 2023)
S_0 (m/s)	Theoretical maximal running speed	Maximal sprint-running speed the athlete would reach if mechanical resistances against movement are null. Also represents capability to produce horizontal force at very high running velocities. Equivalent to V_0 (m/s).	**6.23 – 12.09 m/s** Elite male footballers (Morin et al., 2021: Alonso-Callejo et al., 2022: López-Sagarra et al., 2022: Clavel et al., 2023)
AS_{slope}	Overall orientation of the AS profile Computed as: $AS_{slope} = - A_0 / S_0$	Provides an understanding of the relationship between A_0 and S_0 over the entire sprint acceleration distance.	N/A

3.7 Critically analysing GPS profiling techniques

3.7.1 Force-velocity profiling (maximal sprint testing protocols)

GPS units can prove unreliable mainly due to "noise" in the data, particularly apparent when running at high speeds (Scott et al., 2016), and sometimes lack reliability, accuracy, and sensitivity in measuring acceleration efforts which is particularly noticeable at low speeds (<2 m/s) and when assessing inter-unit variability (Buchheit et al., 2014). Therefore, ensuring measurement continuity by individuals using the same GPS units throughout testing is likely to mitigate for potential inter-unit variation. Force-velocity profiles derived from GPS data use linear fitting which is subject to signal quality that varies due to several holistic factors including the environment i.e., weather and stadia (Gray et al., 2010), specific hardware used i.e., sampling rate and positioning type (Varley et al., 2012), and characteristics of the analysis software (Malone et al., 2017a). Reliability of GPS is time and task-dependent with short high-intensity bouts i.e., maximal acceleration or high-velocity running, proving the least reliable or valid (Aughey, 2011). However, this review focused largely on GPS units sampling at 1 – 5Hz, reporting that higher sampling rates ≥10Hz significantly increased the reliability of associated measures. Despite the negative aspects associated with using GPS several studies have compared GPS against radar devices to measure sprint force-velocity profiles, using data originating from isolated linear sprint testing. One such study demonstrated issues with GPS units’ accuracy of speed-time measurements during maximal sprint accelerations, suggesting they should not be used for force-velocity profiling (Nagahara et al., 2017). Conversely, recent studies report that 10Hz GPS units provide moderate-to-good accuracy of sprint mechanical variables (Cormier et al., 2023c). Contrariety between these studies may be due to the different types of GPS units utilised, 5Hz and 20Hz for the initial study concluding not to use GPS, and 10Hz for the more recent investigation permitting GPS to be used for force-velocity profiling of maximal sprint efforts. The large error bias was reduced when GPS units with higher sampling rates (≥10Hz) were utilised meaning after discounting the impact of the 5Hz unit on skewing study outcomes, both studies instead report moderate-to-good reliability. Therefore, GPS is proven valid and reliable in determining force-velocity profiles from maximal sprint testing (Lacome et al., 2020: Fornasier-Santos et al., 2022: Clavel et al., 2022).

3.7.2 Acceleration-speed profiling in-situ

The individual acceleration-speed profile in-situ concept (Morin et al., 2021) is based on several weeks of cumulated training data which incorporates methodological prerequisites including adequate density of raw points throughout the speed and acceleration spectrum, and consistent linear regression (Clavel et al., 2023). The minimum amount of data required to provide reliable acceleration-speed profiles deriving from the in-situ method is unknown, with recent observations pointing to >45-90 minutes of competitive game data (Morin et al., 2021). Different studies expressed that acceleration-speed profiles could be reliably estimated from a minimum of 5 to 9 days of tracking data, highlighting the discrepancies in minimum monitoring duration proposed between different studies (Alonso-Callejo et al., 2024: Cormier et al., 2023a). Another study reported that ~45 minutes of in-situ method data is likely not enough to determine maximal theoretical force but does provide reliable insight into maximal theoretical running velocity (Komino, 2022). However, none of these studies incorporated elite male footballers as subjects and GPS units used in the latter study were sampling at 18Hz as opposed to the 10Hz that many elite football clubs’ GPS units work, meaning results should not be generalised or applied to this population. GPS-derived force-velocity profiles require cautious interpretation as prediction error and data breadth act to limit the reliability and relevance of this method in predicting individual acceleration-speed profiles in-situ (Imbach et al., 2022). Reliability of the acceleration-speed profile in-situ is most dependent upon spread of data points i.e., 20-95% of maximum speed included, and is improved when a high percentage of maximum speed i.e., ≥ 95%, is reached (Clavel et al., 2023). Ascertaining the minimum amount of GPS data required for valid and reliable acceleration-speed profile determination will likely provide the basis for more straightforward and streamlined data acquisition, increasing the accessibility of this method to coaches and practitioners.

The benefits of using GPS units for force-velocity or acceleration-speed profiling in-situ are that elite football clubs already have access to the required equipment and staff members are familiar with this technology, and moving towards non-invasive, accessible and efficient athlete monitoring is of pivotal importance in the elite football environment (Morin et al., 2021). The drawbacks relating to inherent GPS reliability should be given adequate consideration but are outweighed by the highly significant and relevant advantages, hence the implementation of GPS force-velocity and acceleration-speed profiling in-situ within the current study.

3.8 Changes in profiles between training and competitive games

3.8.1 Potential contributing factors

After adequately considering the potential drawbacks, exploring possible differences in the acceleration-speed profile in-situ between a training session and a competitive game (MD) is worthwhile as it will provide important insight into potential differences in sprint mechanical output variables and acceleration-speed or force-velocity profiles. The training session used for analysis was 4-days prior to match-day (MD-4) as this typically exhibits the highest training load, including acceleration and metabolic variables, most closely reflecting values obtained during competitive games (Stevens et al., 2017). Differences in running metrics exist between training and competitive games (Bangsbo et al., 2006), with additional variation in match demands induced by position-specific tactical demands (Carling., 2013: Bangsbo., 2014: Tierney et al., 2016). The latter can be influenced by different tactical formations, with the most notable position-specific alterations in accelerations, decelerations, and high-intensity running amongst wide defensive and midfield players when changing formations (Modric et al., 2020). Training sessions often lack ecological validity including adequate competitive stimuli which during match-play, act to stimulate maximal performance in sprinting tasks, potentially explaining the divergence in running metrics between training and competitive games (Caldbeck, 2019). Weekly schedule, age group, training mode, and contextual factors i.e., level of opposition, have been found to contribute to training and match load variation (Teixeira et al., 2021). Match demands can also vary due to tactical formation on a holistic scale i.e., average and peak match-play demands for the entire squad (Calder & Gabbett., 2022), individual playing style (Trewin et al., 2017), and level of competition (Martin-Garcia et al., 2019). Football-specific fatigue is likely moderated by the factors outlined, acting to impair players' maximal horizontal force production and maximal velocity capabilities within matches (Nagahara et al., 2016). All of these components may contribute to alterations in the spread of acceleration-speed points, altering the percentage of maximum speed (>95%) reached and changing profiles between training and competitive games (Clavel et al., 2023).

3.8.2 Acceleration-speed profile within training and competitive games

Longitudinal observation of acceleration-speed profiles in elite footballers highlighted divergence in relevant sprint mechanical output variables between different training micro-cycle session days and playing position (Alonso-Callejo et al., 2022). The most demanding day in relation to acceleration-speed profiling in-situ variables was MD, in agreement with previous work investigating general workload variables (Oliva-Lozano et al., 2022). However, results identified should not be extrapolated or applied to other elite football teams as contextual factors cause oscillations in physical demands, consequently influencing relevant profiling variables (Aquino et al., 2017: Yi et al., 2019). A study assessing the reliability of individual acceleration-speed profiling in-situ reported that relevant sprint mechanical output variables (A_0 and S_0) did not change significantly dependent on the inclusion of a match in the cumulated GPS acceleration-speed data (Clavel et al., 2023). Unfortunately, the match in question was a non-competitive game, likely influencing ecological validity so results should not be referenced in relation to potential differences in profiles between training and games.

Another study has reported inter and intra-individual differences and fluctuations in acceleration-speed profiles derived from competitive match data throughout the course of the season (López-Sagarra et al., 2022), aligning with studies which have assessed the seasonal changes in force-velocity profiling variables (Haugen., 2018). Caution should be taken when evaluating these results as this is the first study analysing the seasonal acceleration-speed profile meaning future studies with larger samples are required to corroborate or contrast these findings. The competitive season during which data were collected was shortened due to COVID-19 meaning the cumulated profiles may not adequately consider potential changes in acceleration-speed profiles close to the season end, a phenomenon previously reported to occur in force-velocity profiles towards the end of the season (Jiménez-Reyes et al., 2022). To the authors knowledge only one study has compared acceleration-speed profiles in-situ between training sessions and competitive games, reporting the highest A_0 values during games, and the highest S_0 values during both games and training sessions incorporating specific sprint drills (Miguens et al., 2023). This is the first study to consider differences in acceleration-speed profiles in reference to training and games, and used professional rugby union players meaning further studies amongst the elite footballer population are required. Identifying and assessing imbalances in the acceleration-speed profile demands between training and games could be used to inform and prescribe specific training interventions, perhaps acting to mitigate injury risk and improve performance (Edouard et al., 2021: Alonso-Callejo et al., 2022: López-Sagarra et al., 2022: Clavel et al., 2023: Miguens et al., 2023).

3.8.3 Acceleration-speed profiling in-situ vs force-velocity profiling

Acceleration-speed profiles generated from training and competitive games in-situ are comparable to force-velocity profiles derived from isolated linear sprint testing suggesting that these methods can be used confidently and interchangeably to assess relevant profiles and questioning the requirement for time-consuming standardised testing (Cormier et al., 2023b). Participants were elite female footballers, limiting application of these results to the elite male footballer population, hence the need to replicate assessment in this demographic. The acceleration-speed profile in-situ, based on data collected during a 45-minute training session was closely aligned with the force-velocity profile obtained from a single linear sprint test conducted during the same training session (Komino, 2022). Football-specific contextuality was moderated as the training session may not have been representative of the acceleration-speed profile in-situ based on typical match data i.e., 7 vs. 7 on half-pitch during training as opposed to 11 vs. 11 on full-pitch during a match. A recent study purposed that training sessions should incorporate large-sided games to be more representative of competitive matches (Clavel et al., 2023). Whilst accounting for potentially compromised ecological validity these results support the premise that athletes can be 'tested without testing them' (Morin et al., 2021), again interrogating the necessity to conduct single linear sprint testing. This translates to the start of an era for the implementation of regular acceleration-speed and force-velocity profiling derived from GPS data that can be passively collected during training sessions and competitive games (Miguens et al., 2023).

Harnessing the non-invasive nature and maximising the efficiency of the data collection methods outlined above, an extensive review of current literature failed to yield any studies which investigated force-velocity profiles deriving from GPS monitoring of single isolated sprint acceleration efforts during training sessions and competitive games. Athletes starting their maximal sprint efforts at different velocities and only assessing the single effort when the athlete reached maximum velocity are both factors modulated by contextual factors meaning sprint mechanical output variables and resultant force-velocity profiles computed using this method will potentially display high intra and inter-individual variation between different training sessions and competitive games. The inherent reliability issues with GPS units may elicit further obstacles to using this technique, especially as these problems are accentuated by the cut-off speeds i.e., maximum velocity reached from sprint acceleration starting from <2 m/s and ending >7 m/s (Scott et al., 2016: Buchheit et al., 2014) and non-linear nature of sprints (Pino-Ortega et al., 2022) which are incorporated into this method. Despite these drawbacks, this technique could be an alternative to collecting large amounts of cumulated football training and game data over long periods of time, potentially providing equally meaningful and novel insight into force-velocity profiles during training and competitive games.

Figure 3 shows an acceleration-speed profile for a typical elite footballer, generated using the individual acceleration-speed profile in-situ method (Morin et al., 2021). This demonstrates the maximal forward acceleration capability of an individual over the range of their running velocity spectrum, generated from cumulated football practice data collected over a given period. GPS inaccuracies when measuring high intensity accelerations at low speeds coupled with data filtering and smoothing results in a ‘blank area’ less populated with raw data points, visible on individual acceleration-speed profiles, as highlighted with a red outline in the corresponding figure 3. This warrants caution as the highest acceleration values enacted at the start of the sprint and during initial acceleration are not incorporated completely into the computations, meaning the method relies more heavily on the estimation of these values through linear fitting which could potentially induce variation in subsequent sprint mechanical output variables.

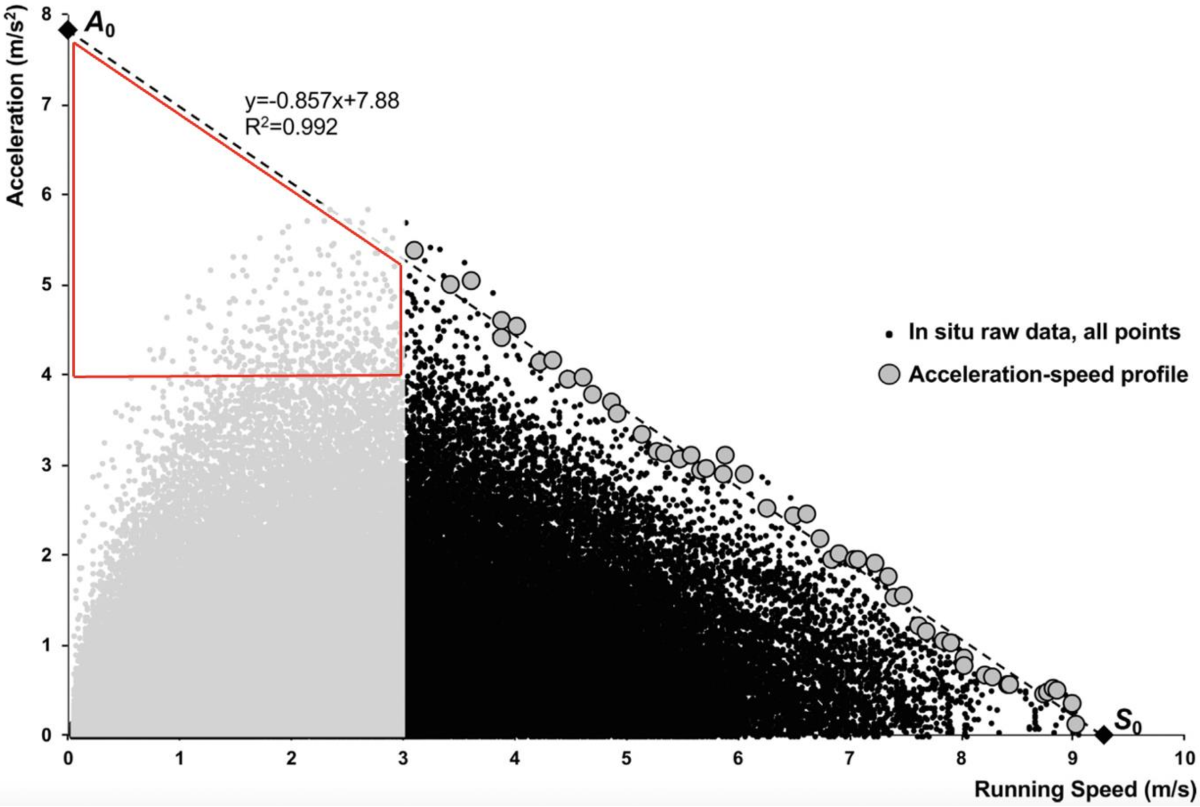

Figure 3: Individual acceleration-speed profile in-situ obtained from the data of 8 training sessions over 2 consecutive weeks in a professional football player (Adapted from Morin et al., 2021). Theoretical maximal acceleration (A_0 = 7.88 m/s^2) and speed (S_0 = 9.19 m/s). Data below the 3 m/s threshold were shaded. Red outline denotes the ‘blank area’ less populated with raw data points, corresponding to high intensity accelerations at low speeds.

3.9 Hamstring injuries and profiling in elite football

3.9.1 Risk factors and propagation

A multitude of potential risk factors including sprinting kinematics contribute to hamstring strain injury (HSI), the primary mechanism of hamstring muscle injury (HMI) (Green et al., 2020). The typical pattern of HMI occurrence in professional football is during non-contact or indirect contact such as during sprinting or lunging actions which require rapid movements with high eccentric demands of the posterior thigh (Gronwald et al., 2022). High-speed running actions have been found to purpose around 70% of HMIs sustained in elite football (Ekstrand et al., 2012). The eccentric brake-driven model of hamstring function is theorised to decelerate knee extension and enhance tolerance of high mechanical loads in the late-swing phase of sprinting with lengthening of the MTU commonly interpreted as an eccentric action of the hamstrings, consequently leaving the hamstrings vulnerable to injury (Van Hooren & Bosch., 2017). Hamstring MTU functioning during sprinting is intricate and dependent upon complex interactions between several variables including musculoskeletal kinematics and kinetics, muscle activation patterns and the neuromechanical regulation of tensions and stiffness, and loads applied by the environment (Kalkhoven et al., 2023). Sprint running mechanics directly regulate HSI risk through the interaction between multiple kinematic and kinetic features acting to influence the magnitude of applied strain contributing to HMI development (Bramah et al., 2023). Hamstrings are subjected to considerable anterior pelvic tilt during the initial steps of sprint running which induces high hip flexion angles, resulting in longer biceps femoris muscle-tendon lengths and faster lengthening velocities, contributing to increased HSI occurrence during acceleration efforts (Astrella et al., 2024: Gurchiek et al., 2024). Experimental and modelling studies investigating various kinematic parameters have associated lumbo-pelvic control (Schuermans et al., 2017b), anterior-pelvic tilt (Schuermans et al., 2017a: Mendiguchia et al., 2024), forward trunk lean (Kerin et al., 2022), trunk lateral flexion (Kenneally-Dabrowski et al., 2019), and maximal hip flexion angle (Daly et al., 2016) with HSI, potentially contributing to HMI occurrence. Most of these studies utilised track and field athletes or elite rugby players as participants, limiting the application of findings to the elite male footballer population.

3.9.3 Profiling and retrospective HMI risk

When returning to play after previous HMI, players immediately presented with decreased F_0 alongside no change in V_0, meaning sprinting performance was impaired (Mendiguchia et al., 2016). A prior study identified improvements in horizontal force production and acceleration capacity 2-months post-return to play (Mendiguchia et al., 2014). A more recent study also reported horizontal strength deficits following injury (Marine et al., 2023). These findings should be interpreted with caution as the first study only incorporated two players, of which only one was a male professional soccer player, and the maximal sprint protocol was conducted over a distance of 50-m, thus limiting the application of results to the elite male footballer population and inhibiting comparison between studies as most other research in this area has either used 30 or 40-m sprint acceleration protocols (Romero-Franco et al., 2017: Lahti et al., 2020: Edouard et al., 2021: Jiménez-Reyes et al., 2022). The other studies sampled larger numbers of players, but they were semi-professional, again compromising the application of outcomes to the elite male footballer population as sprint mechanical output variables differ depending on level of practice i.e., semi-professional players vs professional or elite players (Haugen et al., 2020: Jiménez-Reyes et al., 2018).

Research assessing seasonal changes in force-velocity profiles amongst elite male soccer players have reported meaningful differences in F_0, V_0, and FV_{slope} throughout the season (Haugen., 2018) and compromised sprint mechanical output variables (F_0 more so than V_0), towards the end of the competitive season, perhaps increasing HMI risk (Jiménez-Reyes et al., 2022). However, the prior study did not clarify the exact time point that sprint testing protocols were conducted during each of the distinct 'testing time-points' throughout the season meaning variation in force-velocity profiles within the broad testing periods was not accounted for. The latter study identified fluctuations in the sprint force-velocity profile during the in-season period, but all data were collected from a single elite football team, preventing extrapolation of results to the wider elite football context. Seasonal changes in acceleration-speed profiles amongst elite male soccer players have been reported, with A_0 appearing to be more sensitive to change over the season than S_0 (López-Sagarra et al., 2022), concomitant with the seasonal changes in force-velocity profiles (Jiménez-Reyes et al., 2022). This study has several limitations including its novelty meaning no other literature exists to corroborate or contrast results, players were classed as elite but were from a team competing in the Russian Premier League – a division with limited research base, thus comparing relevant data with other 'elite' teams and leagues is thwart with uncertainty, and the season analysed was shortened due to COVID-19 meaning potential changes in acceleration-speed profiles close to the season end, a phenomenon previously reported to occur in force-velocity profiles towards the end of the season (Jiménez-Reyes et al., 2022) could not be investigated.

3.9.4 Profiling and prospective HMI risk

Few studies have quantified prospective HMI risk in conjunction with fluctuations in sprint mechanical output variables deriving from force-velocity profiling, mainly due to the multifactorial nature of HMI occurrence (Lahti et al., 2020). One study identified that for every 1 N.kg decrease of F_0 there was 2.67 times higher risk of sustaining a new HMI (Edouard et al., 2021) whilst another reported that players who showed reductions in F_0 between screenings had 2.78 times higher odds of HMI occurrence (Edouard et al., 2024). However, the number of measurements and testing execution was different throughout the season depending on the teams and players sampled which limits evaluation of changes in sprint acceleration mechanical outputs within the season and over time in relation to new HMI occurrence. Sprint acceleration mechanical outputs were only analysed during linear sprinting, but hamstring injuries can occur during movements other than sprinting including change of direction, tackling overstretching, or kicking (Ekstrand et al., 2012). This simple measurement is not an assessment of specific muscles that contribute to acceleration, failing to incorporate sprint running technique (Schuermans et al., 2017a) or other potential injury risk factors including neuro-muscular inhibition (Opar et al., 2012) and altered lumbo-pelvic control (Mendiguchia et al., 2017) into consideration meaning this has been proposed as a complementary, sprint-specific component among other potential injury risk factors. In addition, the time from previous hamstring injury was not provided, a factor identified in previous research to mitigate horizontal force production and the occurrence of a new hamstring injury (Mendiguchia et al., 2016). The Sprint Mechanics Assessment Score (S-MAS) is a qualitative movement screening tool which has recently been developed to evaluate sprint running mechanics which may influence HMI risk, incorporating 12 kinematic parameters to assess the overall movement quality of an individual's sprint running mechanics (Bramah et al., 2024). This tool integrates factors reported to be most closely associated with HMI using anecdotal evidence from practitioners and quantitative research, providing a holistic measure of sprint mechanics, but valid and reliable assessment requires training and possibly depends on the testers being highly experienced in the field of biomechanics research.

The extent to which isolated hamstring exercises replicate hamstring functioning when sprinting is questionable. Commonly used hamstring strengthening exercises including the Nordic hamstring exercise, explosive laying kick, and upright hip extension do not sufficiently activate the hamstring muscles (Tillaar et al., 2017), with maximal sprinting being the only exercise to induce adequate hamstring muscle activation (Prince et al., 2021). Recent research emphasises that task-specific, individualised, and maximal sprinting activity should be incorporated into effective HMI management programmes (Edouard et al., 2023: Edouard et al., 2019: Malone et al., 2017b). This is reinforced by a systematically lower incidence of match hamstring injuries in elite football when >95% maximal sprint speed exposures were programmed into training sessions (Buchheit et al., 2023). The direct practical implementation of regular force-velocity profiling into a multifactorial hamstring injury management protocol (Lahti et al., 2020) as part of a biopsychosocial individualised approach can attenuate several issues including long-term programme compliance which are currently experienced within elite football environments (Ayala et al., 2019). Assessing and monitoring elite football players’ individual force-velocity or acceleration-speed profiles is integral to both injury management and return to play protocol development (Morin et al., 2021: Clavel et al., 2023), hence the importance of demonstrating the reliability and validity of relevant profiling techniques. Imbalances in force-velocity and acceleration-speed profiles in situ variables, alongside deviation in these variables from squad norms potentially contribute to increased injury risk (Edouard et al., 2024: Clavel et al., 2023). Implementing this premise, prospective HMI risk can be 'flagged' by plotting acceleration-speed profile in-situ variables (A_0 and S_0) for each individual player in relation to the squad averages for relevant metrics during the training session and competitive game. The resultant scatter plots create charts split into four 'risk quadrants', with larger imbalances between the variables and deviation further away from squad average values (centre of the quadrant chart) potentially indicating higher risk of sustaining HMI. Figure 4 provides a simplified example quadrant chart and interpretation of potential prospective HMI risk levels or 'flags' associated with the different areas of the plot.

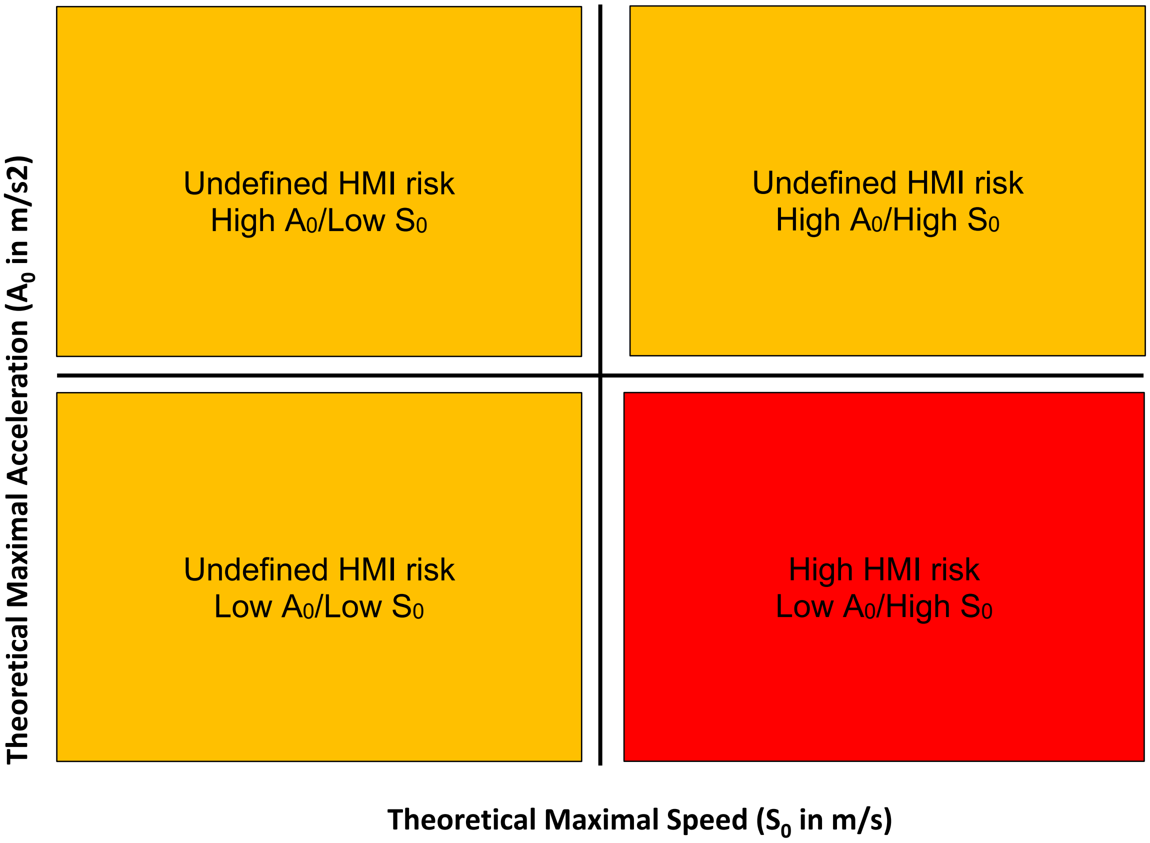

Figure 4: Acceleration-speed profiling in-situ quadrant chart with highlighted risk areas or 'flags'. Axis crossover determined by squad averages. Area of 'high HMI risk' based on previous research investigating the association between reduced F_0/A_0 and increased V_0/S_0 with hamstring injury incidence (Edouard et al., 2021: Edouard et al., 2024).

4.0 Methods

4.1 Subjects

Twenty-nine elite youth football players from the academy of an English Premier League team (male: 29, mean ± SD: age 18.04 ± 1.35 years, height 1.79 ± 0.07 m, body mass 74.98 ± 7.12 kg), free from illness and injury, volunteered to participate in this study comprising of an observational cross sectional within and between-subjects design with retrospective analysis. Players were classified as ‘tier 3 – highly trained/national level’ following recently proposed framework as they were team-sport athletes competing in national-level competitions (1-2 x weekly), engaged in nearly-maximal to maximal training (3-4 x weekly) with the intention to compete at the highest level and highly proficient in football-specific skills (McKay et al., 2021). Goalkeepers were excluded from the study as they participated in separate training and their in-game movement demands differ to that of outfield players. Players were asked to refrain from excessive eating 2 hours before testing sessions, drinking alcohol 24 hours before testing, and wear their normal football boots. Familiarisation protocol was not required for the players as they were regularly exposed to maximal sprints, but pilot testing was conducted prior to study commencement to habituate the researcher with data collection techniques. Data was recorded anonymously by randomly assigning players study numbers (MAPAR 1-29) before testing commenced. Players gave written informed consent to participate in this study, which was approved by Lancaster University Medical School, in accordance with the seventh revision of the Declaration of Helsinki (64th WMA General Assembly., 2013).

4.2 Experimental Protocol

Study 1 consisted of an initial 40-m maximal sprint testing protocol (03/02/2023 – in-season) which was conducted utilising a combination of the MySprint app and force-velocity profile calculation spreadsheet (Morin & Samozino., 2019) alongside GPS monitoring. This was followed by a validity and reliability study comprising of a 30-m maximal sprint testing protocol (01/07/2023 – early pre-season), simultaneously measured using the radar device, MySprint app, and GPS unit. Players completed a standardised 10-minute warmup implemented by the academy strength and conditioning coach which consisted of a general pulse raiser (jogging), acceleration drills, and two progressive intensity 30 – 40-m sprints (70 and 80% effort), resembling protocols in previous research (Mendiguchia et al., 2014). Each player completed two maximal sprints, separated by passive rest lasting the length of time it took other members of the team to complete their runs (around 2 – 3 minutes). Sprint starts were standardised, with all players starting from a two-point staggered-stance position (Fernández-Galván et al., 2021). All players were given the instruction to run as fast as they could through the end of the marked track and quickly move off the runway. Testing protocols were conducted at the start of team training sessions, both corresponding to MD-4 as this typically exhibits the highest training load, most closely reflecting values obtained during competitive games (Stevens et al., 2017: Oliva-Lozano et al., 2022). Study 2 involved post-analysis of variation in force-velocity profiles derived from GPS data of the 30 and 40-m maximal sprint tests. For studies 3 and 4, data acquisition included deriving acceleration-speed profiles in-situ from the GPS data collected during the remainder of the training session MD-4 (03/02/2023 – in-season), and from the competitive game played the following weekend (07/02/2023 – in-season). This was to ensure that GPS data was collected within a reasonable time frame considering potential intra and inter individual variation in acceleration-speed profiles in-situ, reported to fluctuate week-to-week (Alonso-Callejo et al., 2022: Clavel et al., 2023), thus allowing valid and reliable comparisons in profiles between training and competitive games. The training session used for GPS data collection consisted of a medium-sided game lasting 45-minutes (8 vs. 8 + 2 GKs). The maximal sprint testing, training session, and competitive game were performed on outdoor natural grass and recorded for each athlete utilising 10-Hz GPS units (APEX Pro, STATSports, Northern Ireland). GPS units were placed between the player’s scapula using the manufacturers vest, fitted securely to avoid device movement, and were activated 15-minutes prior to the warm-up to ensure good signal quality. The horizontal dilution of precision of the signal and the number of satellites per session were 0.8 ± 0.1 and 17.4 ± 1.2, respectively, which characterised good GPS signal quality (Malone et al., 2017).

4.2.1 Studies 1 and 2 – Maximal Sprint Testing Protocols

4.2.1.1 40m – MySprint app/Spreadsheet combination and GPS

Players were recorded performing two maximal 40m sprints on a natural grass pitch with an iPhone XR (Apple Inc., Cupertino, CA, USA) by the study lead (highly experienced in sprint testing video footage capture) using the built-in standard HD video function (1080p at 60FPS), and individual GPS units. Maximal sprint videos were subsequently imported into the MySprint app (Pedro Jiménez-Reyes., 2016, version 2.0.1). The MySprint app does not have the capability to determine sprint mechanical output variables or resultant force-velocity profiles directly from 40-m sprints meaning the MySprint app was used to calculate split times which were input into a force-velocity profile calculation spreadsheet (Morin & Samozino., 2019) to provide sprint mechanical variables and force-velocity profiles. The straight-line 40m sprint track was clearly marked using cones and flat markers with six visible vertical marker poles placed along the runway from the start at 5.49m (5m), 10.32m (10m), 15.16m (15m), 20m (20m), 29.68m (30m) and 39.36m (40m) to account for parallax – the effect whereby the position or direction of an object appears to differ when viewed from different positions i.e., through a camera lens. Players’ shorts contrasted the vertical marker poles, making it easier to locate the hip COM against the pole. The phone camera was placed on a tripod in landscape orientation, perpendicular to the runway, 18m away from the 20m middle vertical marker pole. Tripod height was 1m to align roughly level with the players' hip COM (Romero-Franco et al., 2017). Figure 5 details the equipment setup for the 40-m maximal sprint testing protocol.

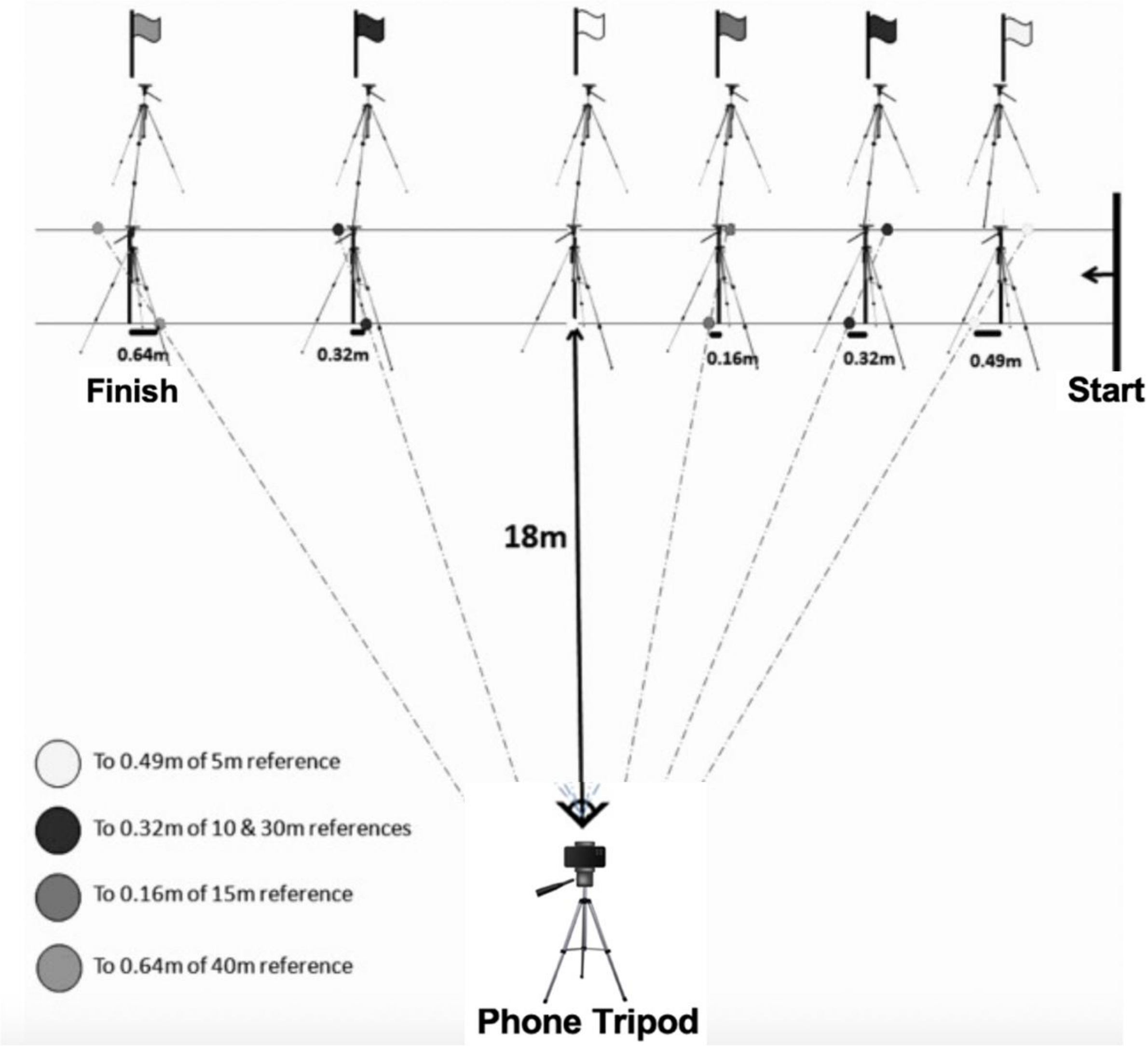

Figure 5: 40-m maximal sprint testing protocol equipment setup
(Adapted from Romero-Franco et al., 2017)

4.2.1.2 30m – Validity and reliability study (Radar device/MySprint app/GPS unit)

Maximal sprint testing protocol was simultaneously measured using the radar device, MySprint app, and GPS unit. Following the same process as outlined in the above section, players were recorded performing two maximal 30-m sprints on a natural grass pitch using a smartphone with slight methodological nuances noted below. Maximal sprints were analysed using the MySprint app (Pedro Jiménez-Reyes., 2016, version 2.0.1), to directly determine sprint mechanical output variables and subsequent force-velocity profiles. The straight-line 30m sprint track was clearly marked using cones and flat markers with six visible vertical marker poles placed along the runway from the start at 5.57m (5m), 10.28m (10m), 15m (15m), 19.72m (20m), 24.43m (25m), and 29.15m (30m) to account for parallax. The phone camera was placed on a tripod in landscape orientation, perpendicular to the runway, 10m away from the 15m middle vertical marker pole. Recording using the smartphone was conducted by the lead academy sports scientist who had previous experience in sprint testing video footage capture (able to smoothly and level pan over the course of the maximal sprint distance).

The radar device (Stalker ATS Pro II; Applied Concepts, Plano, TX, USA) measured instantaneous velocity at a sampling rate of 46.875 Hz and was placed on a tripod 10-m behind the athletes at a height of 1-m, corresponding approximately to the players' hip COM (Morin et al., 2012). Recording using this device was enacted by the study lead who was experienced in radar device data capture. Individual GPS units were also recording the sprints. The sprint for each player which had clean and standardised capture by all equipment types (radar device, MySprint app, and GPS unit) was used for further analysis i.e., the radar device was recording properly, video footage captured the start for MySprint, and GPS data was valid. Concerning inter-tester reliability when using the MySprint app, the primary rater (study lead) was highly experienced in sprint testing video footage capture and the use of the MySprint app whereas the second rater (lead academy sports scientist) had previous experience in sprint testing video footage capture but not specifically using the MySprint app. Prior to MySprint app analysis the two raters partook in basic app orientation and practiced analysis of several example sprints, following the same instructions outlined in the following section 4.2.1.2.2. Figure 6 details the equipment setup for the 30-m maximal sprint testing protocol.

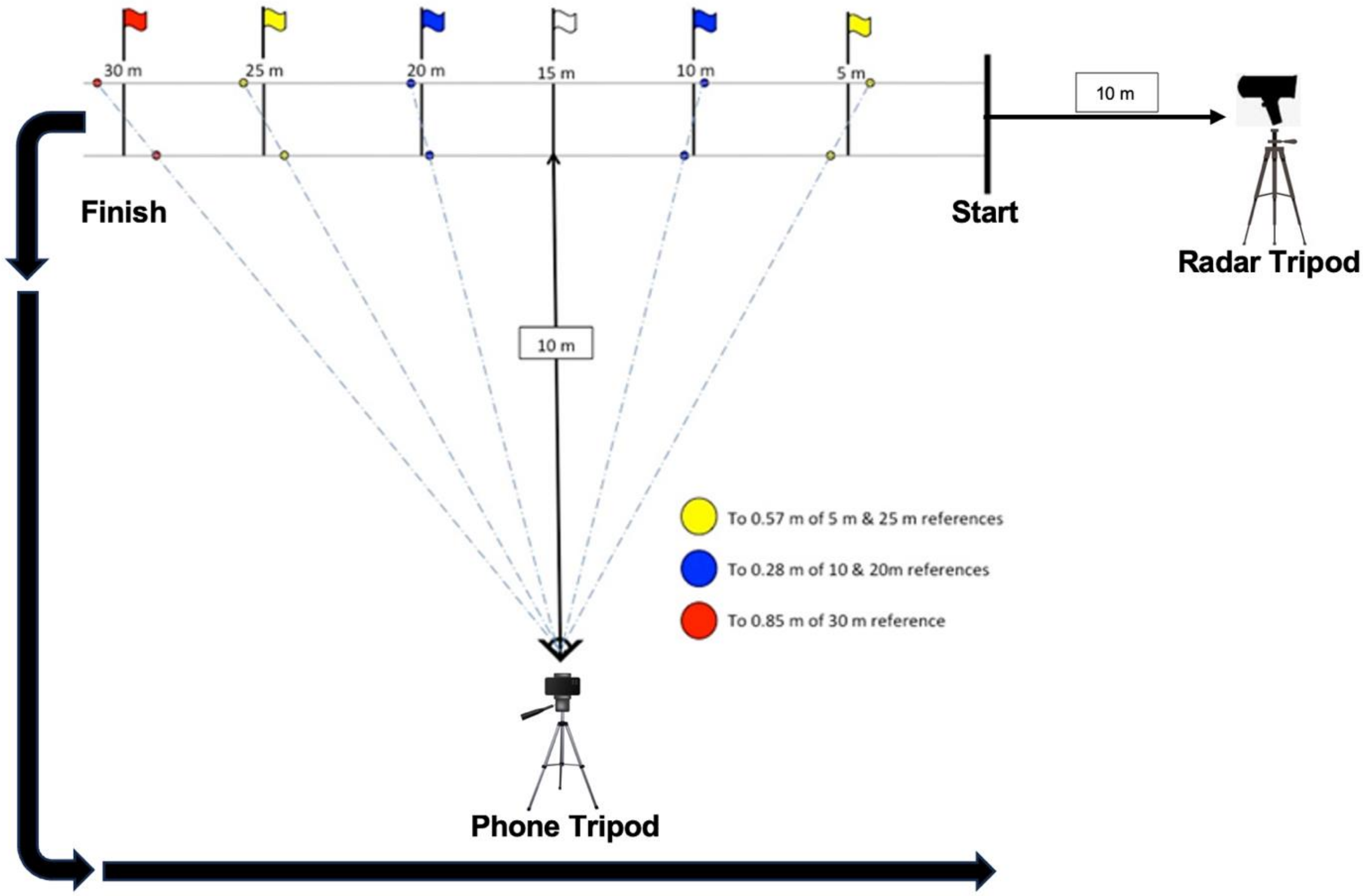

Figure 6: 30-m maximal sprint testing protocol equipment setup (Adapted from Jiménez-Reyes., 2016). Arrows at finish denote direction players were instructed to return to the start – exiting the radar field and passing behind the camera to avoid confounding.

4.2.1.2.1 GPS force-velocity analysis (Isolated Maximal Sprint Testing)

Individual GPS units were continuously recording, capturing both 30 and 40-m maximal sprints during their respective testing protocols. Following the session, data was downloaded using the manufacturers software (Sonra, STATSports, Northern Ireland), isolated maximal sprint efforts were ‘clipped’, and custom Microsoft Excel export created containing relevant metrics required for force-velocity profile calculation (time, speed, acceleration) for both maximal sprints performed during each testing protocol. Time data was converted from 24HR format to seconds at 0.1s intervals. The start of the sprint was identified as significant increase on the speed plot i.e., >0.2 m/s, to max velocity reached. Excel scatter plots with smooth lines and markers were created for each sprint to visualise both maximal sprints performed by each player. Time (s) and speed (m/s) data were copied and pasted into the GPS force-velocity spreadsheet (Morin., 2022) to calculate sprint mechanical output variables and subsequent force-velocity profiles for each maximal sprint performed (Alonso-Callejo et al., 2024).

4.2.1.2.2 MySprint force-velocity analysis procedure

The start of the sprint was defined as the moment at which body movement started, specifically the first instance of lower-limb motion from standstill preceding the onset of the sprint start (detected via visual inspection with MySprint (Morin., 2017). The hip COM was located at the centre of the pelvis, identifiable during video footage analysis. The frames were then selected in which each players hip COM was aligned with each of the six vertical marker poles. Player’s body mass, stature, and split times were used by the MySprint app to calculate F_0 (N/kg), V_0 (m/s), V_{max} (m/s), and FV_{slope}, ultimately determining individual force-velocity profiles, using previously validated formulas (Samozino et al., 2016). Individual differences in body mass were accounted for by incorporating body mass into relevant metric calculations i.e., N/kg.

4.2.1.2.3 Radar device force-velocity analysis procedure

During the session, data was recorded using a laptop running Stalker ATS System™ software (Version 5.1.1, Applied Concepts, Inc., Texas, USA). Radar data acquisition was started once the player was in the start position, prior to the moment at which body movement started to fully capture the sprint start and ended once the player had passed the finish. The raw data capture file for each maximal sprint was then manually saved to the computer. Following the testing session these files were manually processed in the software system by deleting all data recorded prior to the start and after the finish of each sprint and classifying all trials as 'acceleration runs' thereby forcing the start of the velocity-time curve through the zero point (Simperingham et al., 2019). Filtering type selected was 'Dig Medium'. The original files (.rda) were converted into a different format (.rad or .xlsx), the start of the sprint was identified as significant increase on the speed plot i.e., >0.2 m/s (0.72 km/h), to max velocity reached. Excel scatter plots with smooth lines and markers were created for each sprint to visualise both maximal sprints performed by each player. Time (s) and speed (km/h) data were copied and pasted into the radar force-velocity spreadsheet (Morin., 2022) to calculate sprint mechanical output variables and subsequent force-velocity profiles for each maximal sprint performed.

Standardised >0.2 m/s increase in speed threshold was used to denote the sprint start for both the radar and GPS units. For most players the root-mean-square error value corresponding to these cut-offs was <0.2 thus indicating good reliability and validity (Chai & Draxler., 2014). Most studies in this area have also incorporated these thresholds, enabling valid and reliable comparisons in relevant sprint mechanical output variables (Romero-Franco et al., 2017: Simperingham et al., 2019). The higher sampling rate of the radar device prevented significant differences in speed between samples meaning a higher speed threshold i.e., >0.5 – 1 m/s would have made it difficult to determine the actual sprint start. Acceleration (m/s^2) thresholds were not used as these devices can be unreliable at measuring acceleration at low speed, and these secondary values are derived from the primary raw speed data anyway (Scott et al., 2016: Buchheit et al., 2014). Relevant sprint mechanical output variable and force-velocity profile calculation spreadsheets can be accessed in the 'Resources' section.

4.2.2 Studies 3 and 4 – GPS acceleration-speed profiling in-situ

Individual GPS units were continuously recording during the training session MD-4 and the competitive game played the following weekend (MD), generating raw speed-time data. Linear interpolation was used to provide ‘missing’ speed data points based on the 10 Hz GPS data already assembled. Raw speed data was smoothed using Savitzky-Golay signal filtering algorithm which incorporated ‘missing data’ from the STATSports output, similar to the ‘low-pass’ filtering techniques utilised in similar acceleration-speed profiling studies (Morin et al., 2021: Clavel et al., 2023). Acceleration values at each point were calculated as the rate of change of the filtered speed, according to acceleration being defined as the change in speed over a given change in time (Blazevich., 2017). Maximal speed-acceleration values were derived from the five maximal values of acceleration performed for each 0.2 m/s speed subinterval (3 m/s to maximal speed). A 3 m/s threshold was used as maximal values of acceleration are rarely observed below this point, consistent with the notion that at the very first steps of a standing start the COM velocity raises quickly above 3 m/s within the first step (Nagahara et al., 2014: Morin et al., 2019). Five maximal acceleration values at each speed subinterval were used for analysis as opposed to only two maximal values used in similar previous research (Morin et al., 2021: Clavel et al., 2023), likely providing more valid insight into the acceleration values observed at each speed throughout the spectrum. A linear regression line was fitted to these points and residuals analysed, with outlier points (standardised residuals >2 standard deviations away from the regression line) removed, yielding an accurate regression line to delineate the individual acceleration-speed profile in-situ from which several main variables were derived: A_0 (theoretical maximal acceleration in m/s^2) and S_0 (theoretical maximal running speed in m/s), as intercepts of the y-axis and the x-axis, respectively, and the AS_{slope} (overall orientation of the A-S profile), computed as $- A_0 / S_0$.

4.3 Statistics

Statistical analyses were performed using the software package Jamovi (version 2.3.28). Data were checked for normality of distribution using a Shapiro-Wilk test due to the sample size, analysis confirmed data did not follow a normal distribution, necessitating the use of non-parametric tests. Intra-tester reliability from the 30-m (MySprint app) and 40-m (MySprint app to calculate split times and spreadsheet to calculate sprint mechanical variables) maximal sprint testing protocols, reliability of the MySprint app against the calculation spreadsheet to determine force-velocity profiles from sprint split times, and inter-tester reliability were determined using the Wilcoxon Matched Pairs test, RMSE, coefficient of variation (CV), and intraclass correlation coefficient (ICC). ICC was single measure, two-way mixed, absolute agreement parameters (3,1) for intra-tester reliability and average measures, two-way mixed, absolute agreement parameters (3,2) for inter-tester reliability (Hopkins, 2000: Stojiljković et al., 2024). Spearman's rank correlation coefficient was used to demonstrate the concurrent validity in computed sprint mechanical variables between the MySprint app and the calculation spreadsheet. Differences in sprint mechanical output variables (F_0 and V_{max}) between equipment types (radar device, MySprint app, and GPS unit) were examined using a Kruskal-Wallis test and level of agreement between devices was measured using Bland-Altman plots. Equipment reliability was analysed using the Wilcoxon Matched Pairs test, ICC (3,1), RMSE, and CV. Distance-induced variation in sprint mechanical output variables and force-velocity profiles were measured using the Wilcoxon Matched Pairs test. Differences in the acceleration-speed profile in-situ variables (A_0, S_0, and AS_{slope}) between the training session and competitive game were investigated using a Mann-Whitney U test. The same test was used to report differences in relevant profiling variables between the 30m maximal sprint testing protocol (GPS force-velocity profiling: F_0 and V_{max}) and training session (GPS acceleration-speed profiling in-situ: A_0 and S_0). Statistical significance was set at $p < 0.05$.

In the event of a significant result using the Kruskal-Wallis test, Dwass-Steel-Critchlow-Fligner pairwise comparison was applied and epsilon squared (ε^2) effect sizes calculated; 0.01 – 0.059 (small effect), 0.06 – 0.139 (moderate effect) and ≥ 0.14 (large effect) (Cohen, 2016). For the Mann-Whitney U and the Wilcoxon Matched Pairs tests, rank biserial correlation effect sizes were calculated and interpreted as small (0.01 – 0.19), medium (0.20 – 0.49), and large (> 0.50), as reported by Cohen (1992). Effect size calculations indicate the magnitude of effects, which is typically more relevant to athletic performance than statistical significance (Fritz et al., 2012). ICC interpreted as: <0.5 = poor reliability; 0.5 – 0.75 = moderate reliability; 0.75 – 0.9 = good reliability; and >0.90 = excellent reliability (Koo & Li., 2016). CV interpreted as good when < 10% (Buchheit et al., 2011). RMSE interpreted as good when < 0.2 (Chai & Draxler., 2014). Correlation effects interpreted as weak (0.10 – 0.29), moderate (0.30 – 0.49), strong (0.50 – 0.69), and very strong (≥ 0.70) (Hopkins et al., 2009). Several data visualisation techniques were used to report results: descriptive plots, bar charts, scatter plots, Bland-Altman plots, box & whisker plots, acceleration-speed profiles in-situ, force-velocity profiles, and quadrant charts. Raw descriptive data in tables was presented as means ± SD.

4.3.1 Sample size justification and power

Table 4 Sample sizes, inclusion and exclusion criteria for each individual study

Study	**Initial sample size**	**Actual sample size**	**Justification (inclusion/exclusion criteria)**
40-m intra-tester reliability	28	25	Players included if they had completed at least one 40-m sprint. 4 players were excluded from further analysis as video footage failed to capture the sprint start adequately (recording started late).
40-m vs. 30-m distance variation	12	7	Players included if they took part in and had ‘clean’ GPS data capture for at least one sprint in both the 30 and 40-m maximal sprint testing sessions.
30-m intra & inter-tester reliability, MySprint app vs. calculation sheet, validity of MySprint app and GPS against ‘gold standard’ radar device.	12	11	Players included if they had clean and standardised capture by all equipment types for at least one sprint (radar device, MySprint app, and GPS unit).
30-m inter-trial reliability	12	10	Same criteria as above but additional requirement that players completed both sprint repeats with clean and standardised capture.
Acceleration-speed profiling in-situ training vs. competitive game	21	14	Players included if they participated in a minimum of 45-minutes in the training session, 45-minutes in their respective competitive game, and reached > 95% of peak speed (from individualised GPS software thresholds based on cumulated historical training/game data), in both instances (training session and competitive game).
Acceleration-speed profiling in-situ training vs. 30-m sprint testing	16	6	Players included if they participated in a minimum of 45-minutes in the training session, and reached > 95% of peak speed, but additional requirement that players also completed 30-m sprint testing.

Force-velocity profiles derived from GPS data of isolated maximal sprint acceleration efforts during training and competitive games were deemed invalid after considering the limitations outlined in the literature review and initial statistical analysis. These related to the inability to standardise a single isolated maximal sprint acceleration effort, with resultant sprint mechanical output variables and force-velocity profiles modulated by contextual factors, potentially inducing high intra and inter-individual variation between different training sessions and competitive games. Some reliability issues with GPS units likely elicited further obstacles to using this technique, accentuated by the cut-off speeds (<2 m/s – >7 m/s) and non-linear nature of sprints incorporated into this method (Scott et al., 2016: Buchheit et al., 2014: Pino-Ortega et al., 2022). Many of the isolated maximal sprint acceleration efforts performed during training and competitive games failed to start <2 m/s or end >7 m/s and displayed high RMSE values (>0.2) (Chai & Draxler., 2014), preventing inclusion in further analysis.

The minimum amount of GPS data required to provide valid and reliable acceleration-speed profiles in-situ is unknown, with different studies reporting contrasting observations: >45-90 minutes of training or competitive game data (Morin et al., 2021), 5 to 9 days of tracking data (Alonso-Callejo et al., 2024: Cormier et al., 2023a), and ~45 minutes of in-situ method data (Komino, 2022). Players who participated in a minimum of 45-minutes in the training session, 45-minutes in their respective competitive game, and reached > 95% of peak speed (from individualised GPS software thresholds based on cumulated historical training/game data) in both instances (training session and competitive game) were included in further acceleration-speed profile in-situ analysis and comparison. These inclusion criteria were used as players were unlikely to achieve a spread of acceleration points throughout the entire velocity spectrum (3 m/s to maximal speed) from <45-minutes trained or played in competitive game.

An a priori power analysis for study 3 was conducted using the software G*Power version 3.1.9.6 (Faul et al., 2007) to determine the sufficient sample size to ensure to a particular degree of certainty that the study has acceptable power to support the null hypothesis and prevent type II error (Sullivan & Feinn, 2012). The subsequent calculation was based on the Mann-Whitney U test implemented to report differences in relevant profiling variables between the 30m maximal sprint testing protocol (GPS force-velocity profiling: F_0 and V_{max}) and training session (GPS acceleration-speed profiling in-situ: A_0 and S_0). Alpha level was set at 0.05 and effect size at > 0.5 (Cohen., 1992). This output a sample size of 28 which would provide adequate power (80%+) to support the null hypothesis when examining for differences in relevant profiling variables. Due to the implicit constraints of the elite football environment limiting access to participants none of the sub-questions had sufficient sample sizes to provide adequate power, a caveat of most research conducted in this area (Schäfer & Schwarz, 2019).

5.0 Results

5.1 Descriptive data

Table 5 Main variables from 30-m maximal sprint testing (force-velocity profiling) and training or competitive game in-situ (acceleration-speed profiling). Data presented as means ± SD.

	F_0 (N/Kg) or A_0 (m/s^2)	V_{max} (m/s) or S_0 (m/s)
MySprint app	10.10 ± 0.88	7.82 ± 0.30
GPS	7.39 ± 0.49	8.80 ± 0.33
Radar	7.58 ± 1.10	8.89 ± 0.30
Training in-situ (MD-4)	6.50 ± 0.37	8.24 ± 0.59
Competitive game in-situ (MD)	6.48 ± 0.47	8.70 ± 0.41

5.2 Study 1 – Intra-tester reliability

There was no significant difference in F_0 (W = 25, $p > 0.05$) or V_{max} (W = 12, $p > 0.05$) when the MySprint analysis procedure was repeated by the same tester for the 30-m maximal sprint testing protocol. RMSE and CV values for F_0 and V_{max} were 0.19 N/Kg and 2.9%, 0.07 m/s and 0.54%, respectively, both interpreted as 'good' (RMSE < 0.2, CV < 10%). ICC demonstrated good and excellent levels of agreement in the values of F_0 and V_{max} between repeats (ICC = 0.832, CI = 0.508 – 0.951, and ICC = 0.976, CI = 0.871 – 0.994, respectively). Consistency in MySprint app analysis procedure for F_0 (***a***) and V_{max} (***b***) is visualised using descriptive plots in figure 7.

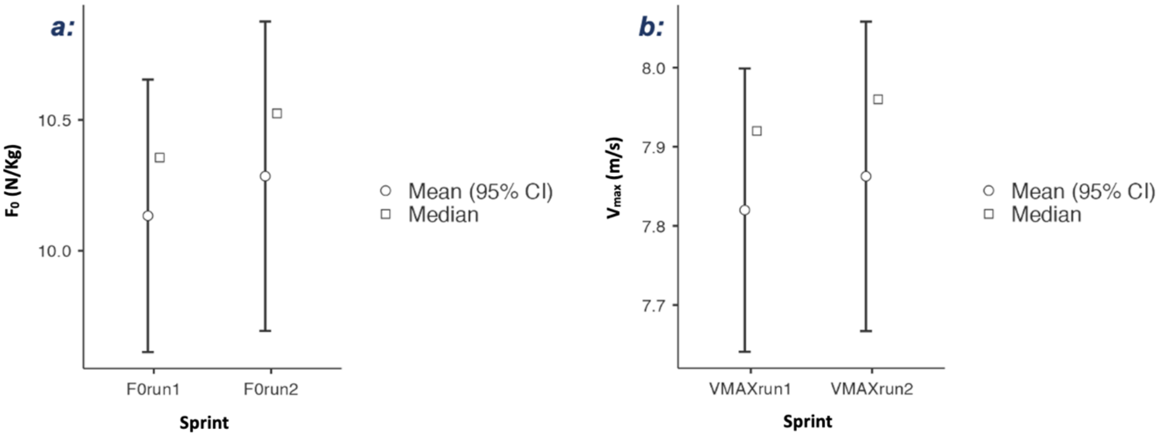

Figure 7: Descriptive plots of Wilcoxon Matched Pairs test raw data including mean and median with error bars denoting range, for F_0 (***a***) and V_{max} (***b***).

There was a significant difference in F_0 (W = 85, $p < 0.05$) and V_{max} (W = 70, $p < 0.05$) with medium to large effect sizes reported (0.477 and 0.569, respectively) when the MySprint app and spreadsheet analysis procedure was repeated by the same tester for the 40-m maximal sprint testing protocol. RMSE and CV values for F_0 and V_{max} were 0.61 N/Kg and 3.81%, 0.41 m/s and 2.64%, respectively, interpreted as ‘poor-to-moderate’ (RMSE > 0.2) and ‘good’ (CV < 10%). ICC demonstrated good and poor levels of agreement in the values of F_0 and V_{max} between repeats (ICC = 0.871, CI = 0.724 – 0.941, and ICC = 0.483, CI = 0.115 – 0.734, respectively). Differences in the MySprint app and spreadsheet analysis procedure outcomes for F_0 (***a***) and V_{max} (***b***) are visualised using descriptive plots in figure 8.

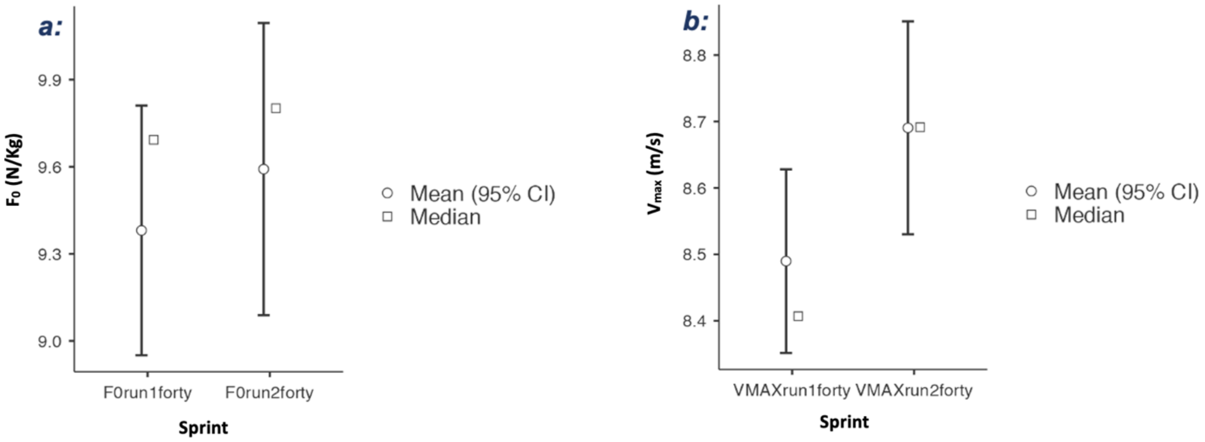

Figure 8: Descriptive plots of Wilcoxon Matched Pairs test raw data including mean and median with error bars denoting range, for F_0 (***a***) and V_{max} (***b***).

5.3 Study 1 – Reliability and validity of MySprint app against calculation spreadsheet

There was no significant difference in F_0 (W = 20, $p > 0.05$) or V_{max} (W = 45, $p > 0.05$) between the MySprint app and the calculation spreadsheet analysis procedures for the 30-m maximal sprint testing protocol. RMSE and CV values for F_0 and V_{max} were 0.08 N/Kg and 0.43%, 0.01 m/s and 0.14%, respectively, both interpreted as ‘good’ (RMSE < 0.2, CV < 10%). ICC demonstrated excellent levels of agreement in the values of F_0 and V_{max} between procedures (ICC = 0.995, CI = 0.983 – 0.999, and ICC = 0.998, CI = 0.994 – 1.000). Spearman’s rank correlation coefficient revealed significant very strong associations in F_0 (rho = 0.964) and V_{max} (rho = 0.991) between the MySprint app and the calculation spreadsheet ($p < 0.05$, rho > 0.7). Concurrent validity in measurement of F_0 (***a***) and V_{max} (***b***) between procedures is visualised using scatter plots and correlation matrix’ in figure 9 overleaf.

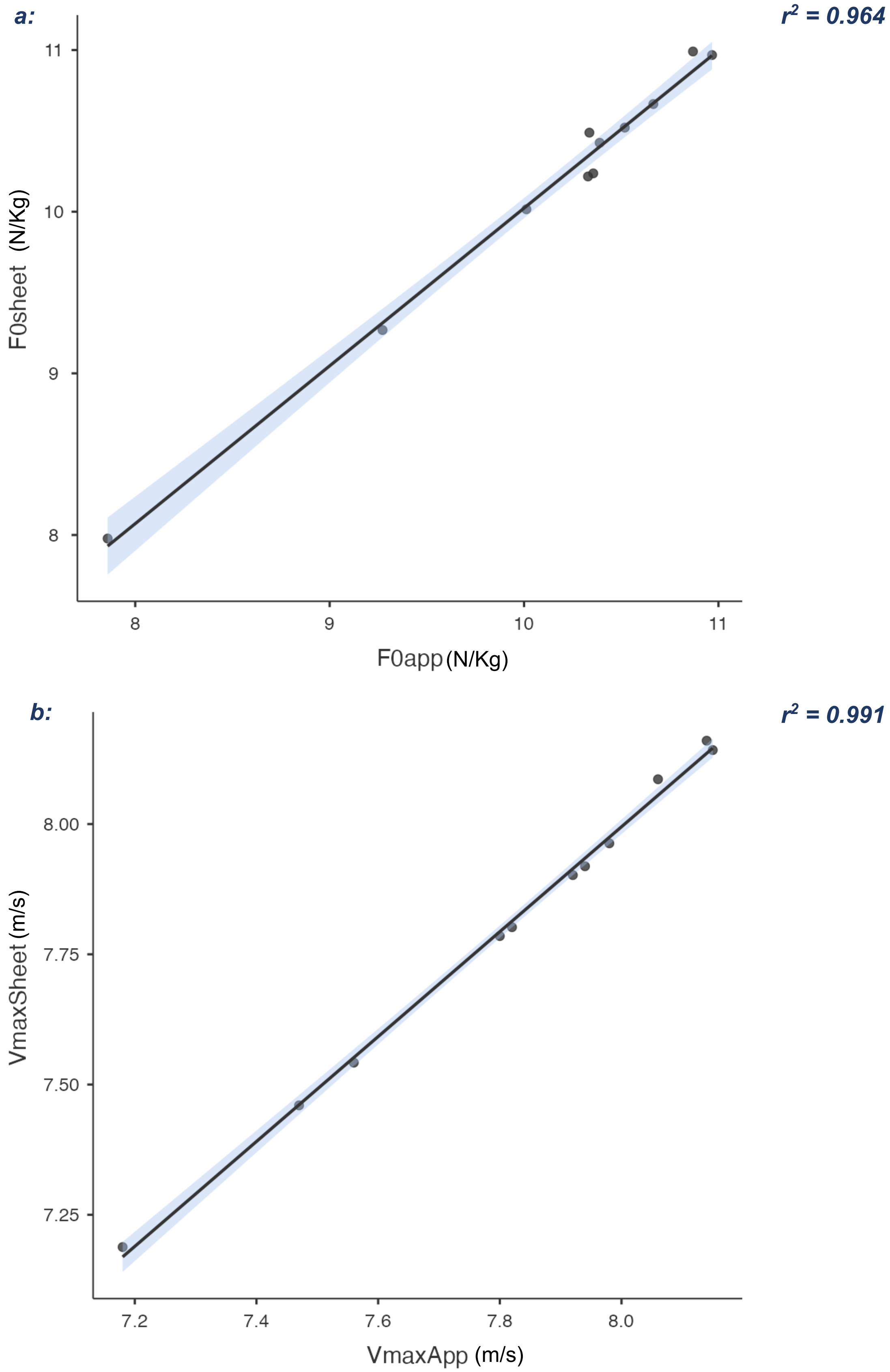

Figure 9: Scatter plots demonstrating the concurrent validity in computations of F_0 (***a***) and V_{max} (***b***) between the MySprint app and the calculation spreadsheet with linear regression line. Shaded area around line of best fit denotes standard error.

5.4 Study 1 – Inter-tester reliability

There was no significant difference in F_0 (W = 26, $p > 0.05$) or V_{max} (W = 12.5, $p > 0.05$) between the two testers performing the MySprint app analysis procedure for the 30-m maximal sprint testing protocol. RMSE and CV values for F_0 and V_{max} were 0.18 N/Kg and 1.04%, 0.06 m/s and 0.42%, both interpreted as 'good' (RMSE < 0.2, CV < 10%). ICC demonstrated excellent levels of agreement in the values of F_0 and V_{max} between the two testers (ICC = 0.986, CI = 0.950 – 0.996, and ICC = 0.988, CI = 0.957 – 0.997). The level of agreement in F_0 (***a***) and V_{max} (***b***) between the two testers is visualised using Bland-Altman plots in figure 10.

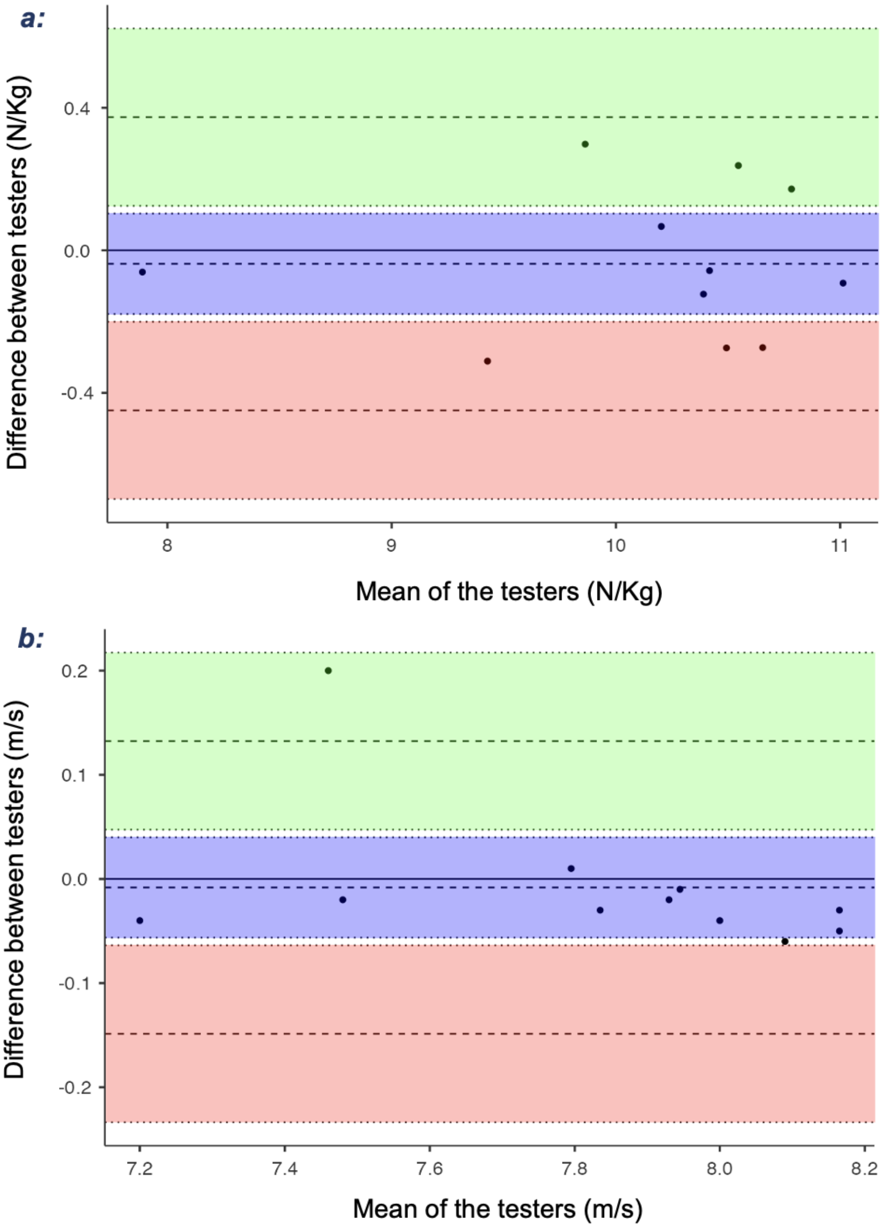

Figure 10: Bland-Altman plots for F_0 (***a***) and V_{max} (***b***) between testers. The central dotted line represents the absolute average difference (bias) between testers, whilst the upper and lower dotted lines represent limits of agreement (±1.96 SD).

5.5 Study 1 – Validity and inter-trial reliability (30-m maximal sprint testing protocol)

5.5.1 Validity of the MySprint app and GPS against ‘gold standard’ radar device

There were significant differences in F_0, V_{max}, and FV_{slope} computed by the MySprint app, radar, and GPS units ($p < 0.05$), with large effect sizes reported ($\varepsilon^2 = 0.621$, 0.684, and 0.781, respectively). Pairwise comparisons reported significant differences in F_0, V_{max}, and FV_{slope} between the MySprint app and radar device ($p < 0.05$), alongside no significant differences in F_0 or V_{max} ($p > 0.05$), but significant differences in FV_{slope} ($p < 0.05$), between the GPS and radar device. Mean F_0 and V_{max} computed simultaneously using the MySprint app, radar device, and GPS units are shown in figure 11. Differences in the FV_{slope} between equipment types are demonstrated by the force-velocity profiles superimposed in figure 12. The level of agreement in F_0 (***a***) and V_{max} (***b***) between the radar device and GPS unit is visualised using Bland-Altman plots in figure 13.

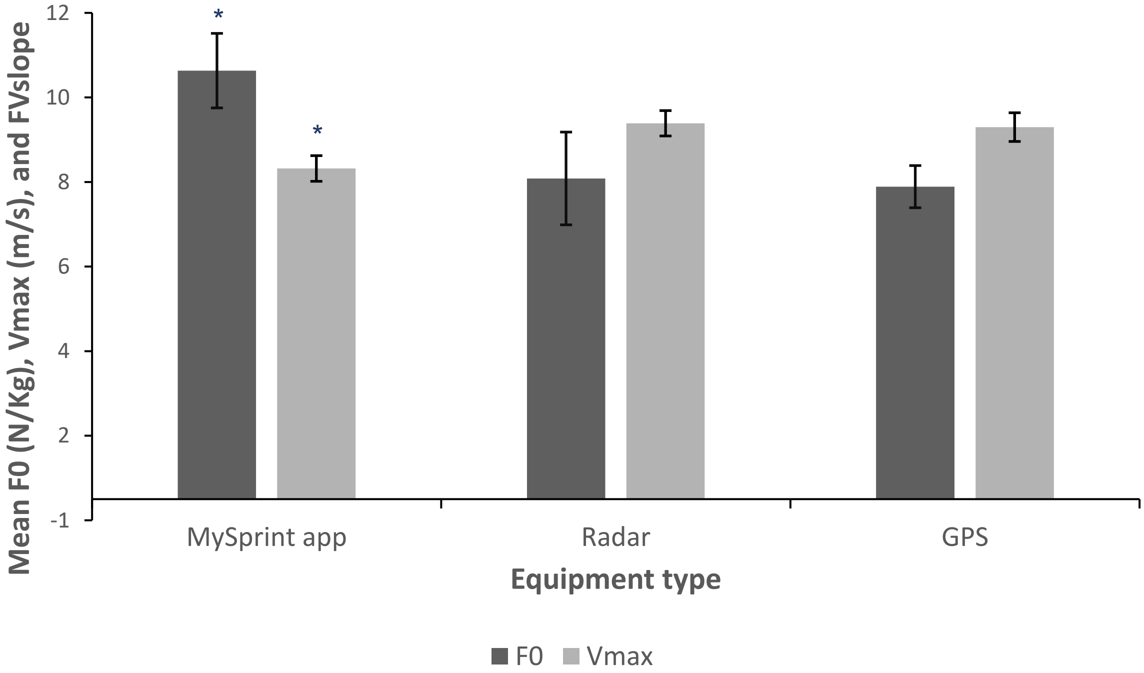

Figure 11: F_0 and V_{max} between equipment types. Data presented as means with error bars denoting SD and * indicating significant difference from radar device and GPS.

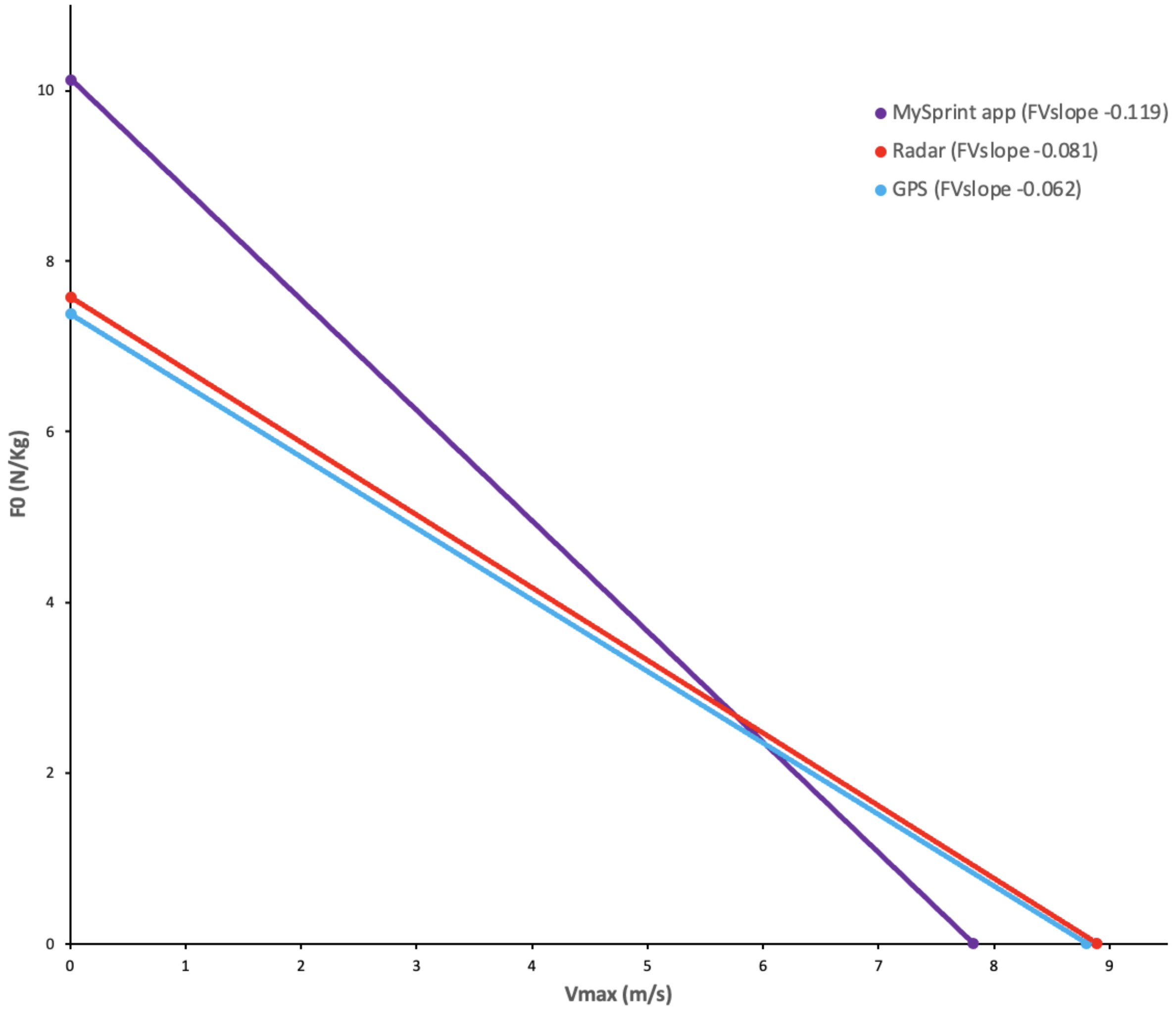

Figure 12: Force-velocity profiles (FV_{slope}) between equipment types

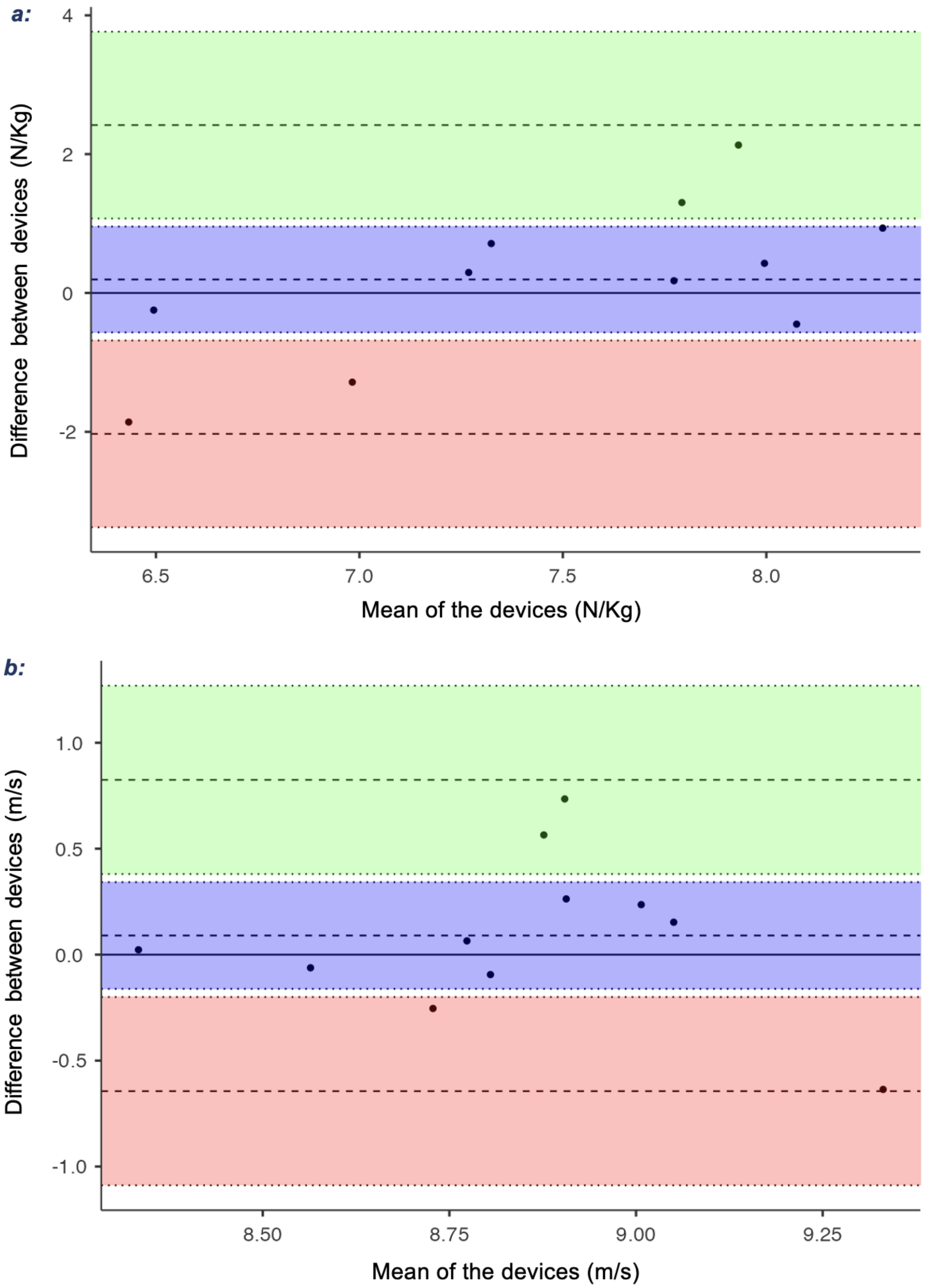

Figure 13: Bland-Altman plots for F_0 (***a***) and V_{max} (***b***) between the radar device and GPS. Central dotted line represents the absolute average difference (bias) between equipment, whilst the upper and lower dotted lines represent limits of agreement (±1.96 SD).

5.5.2 Inter-trial reliability – within equipment between two sprints performed

There were no significant differences in F_0 or V_{max} ($p > 0.05$) between the two sprints performed by each player for all equipment types used (MySprint/Radar/GPS). ICC reported poor and good levels of agreement for the MySprint app (F_0 ICC = 0.285 and V_{max} ICC = 0.865), poor and moderate levels of agreement for the radar device (F_0 ICC = 0.324 and V_{max} ICC = 0.548), and poor levels of agreement for the GPS (F_0 ICC = 0.064 and V_{max} ICC = 0.437) between the two sprints performed by each player. RMSE and CV values for the MySprint app derived F_0 and V_{max} were 0.72 N/Kg and 3.76%, 0.21 m/s and 1.48%, respectively, with all values interpreted as 'poor' (RMSE > 0.2) and 'good' (CV < 10%). Values for the radar device computed F_0 and V_{max} were 1.11 N/Kg and 8.66%, 0.30 m/s and 2.22%, respectively, with values interpreted as 'poor' (RMSE > 0.2) and 'good' (CV < 10%). Outputs for the GPS F_0 and V_{max} were 1.20 N/Kg and 9.59%, 0.40 m/s and 2.64%, respectively, with values interpreted as 'poor' (RMSE > 0.2) and 'good' (CV < 10%). Mean F_0 and V_{max} between sprint repeats, derived from each equipment type are shown in figure 14.

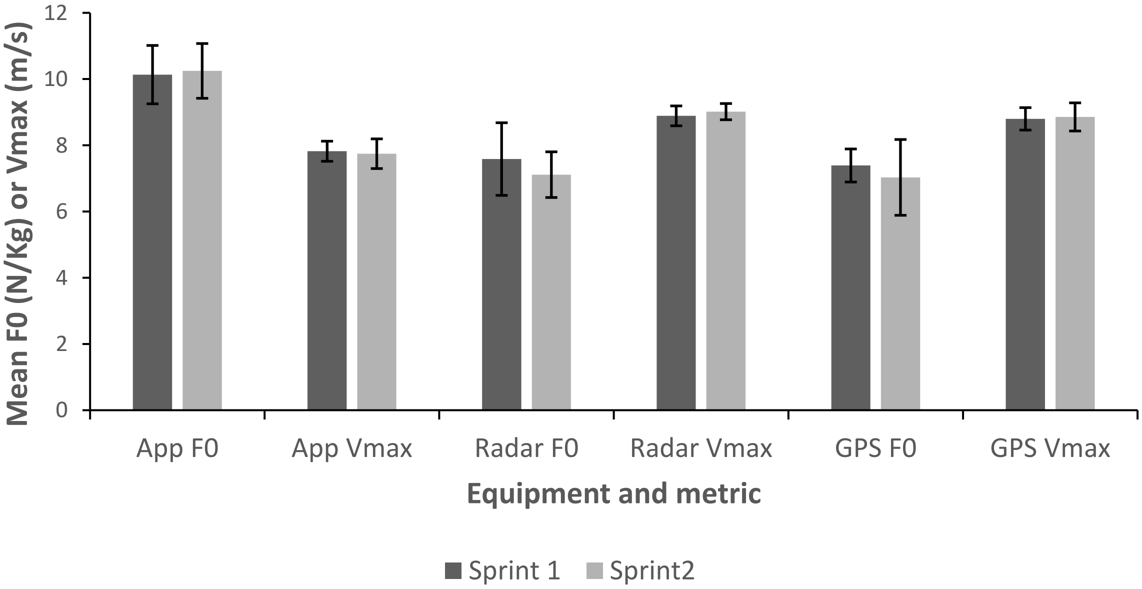

Figure 14: F_0 and V_{max} between the two sprints for each equipment type. Data presented as means with error bars denoting SD.

5.6 Study 2 – Distance-induced variation in force-velocity profiles

There were significant differences in F_0, V_{max}, and FV_{slope} ($p < 0.05$) between the two sprint distances (30 and 40-m), with large effect sizes reported (rank biserial correlation = 0.857, 0.786, and 0.893, respectively). Differences in F_0 (***a***), V_{max} (***b***), and FV_{slope} (***c***) between the sprint distances are visualised using descriptive box and whisker plots in figure 15.

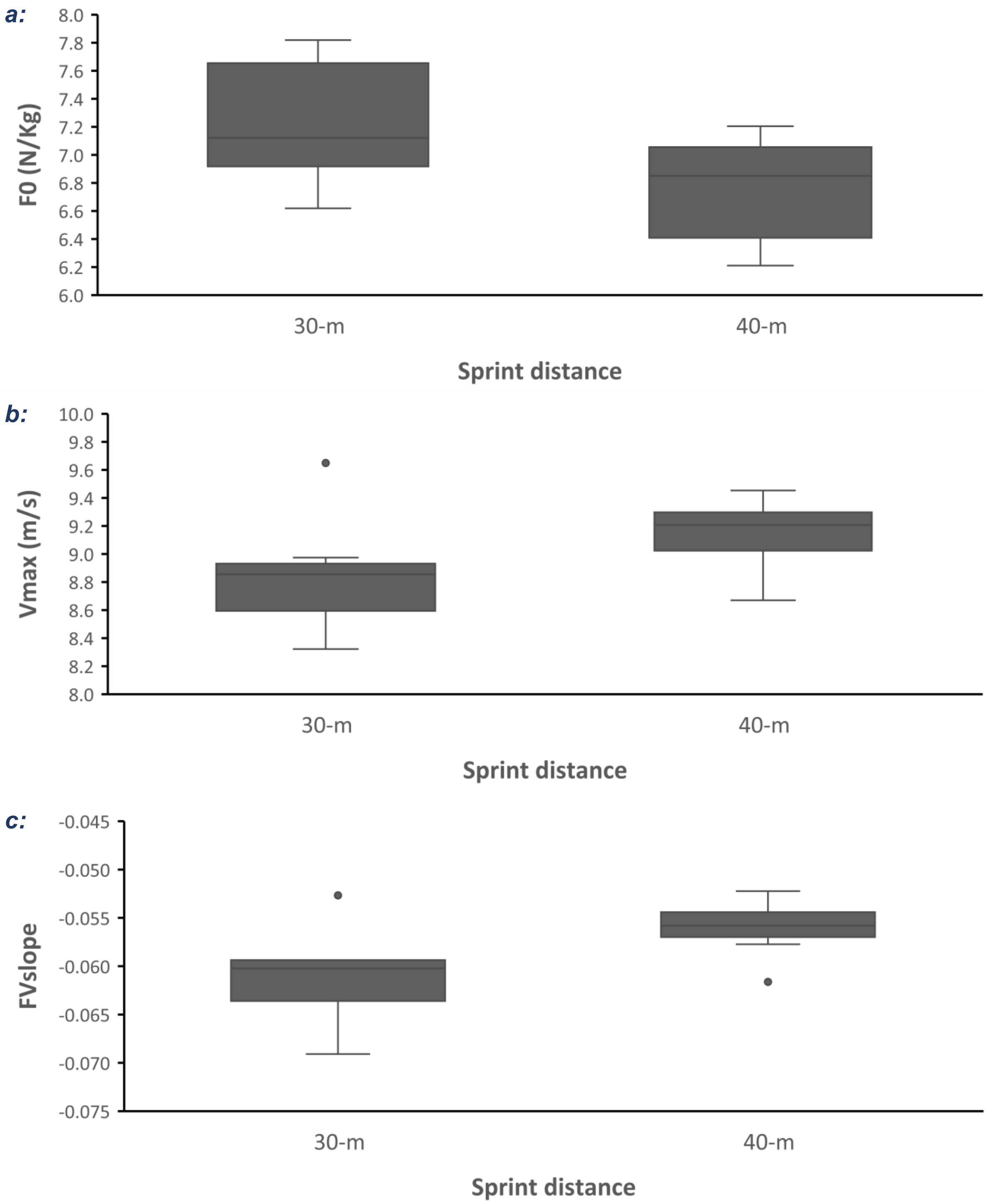

Figure 15: Descriptive box and whisker plots for F_0 (***a***), V_{max} (***b***), and FV_{slope} (***c***) between 30 and 40-m sprint distances. Inclusive medians with circles denoting outliers.

5.7 Study 3 – Acceleration-speed profiles in-situ (training vs. competitive games)

There were significant differences in S_0 ($p < 0.05$), with medium effect size reported (rank biserial correlation = 0.479), but no significant differences in A_0 or AS_{slope} ($p > 0.05$) between the training session and competitive game. Mean A_0, S_0, and AS_{slope} between the training session and competitive game are shown in figure 16.

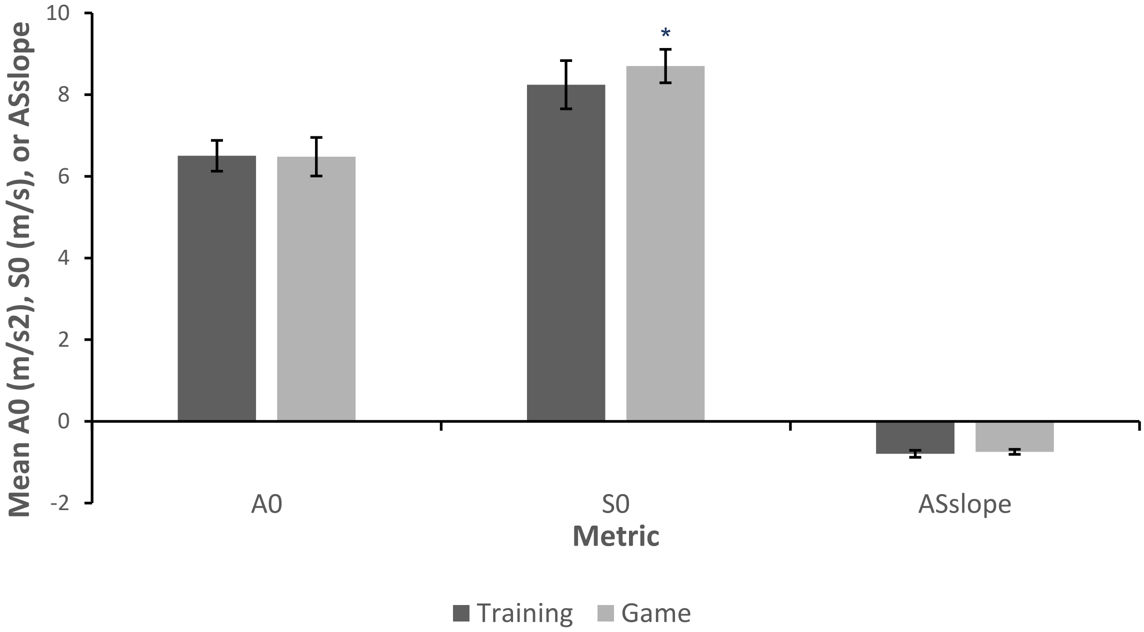

Figure 16: A_0, S_0, and AS_{slope} between the training session and competitive game. Data presented as means with error bars denoting SD and * indicating significant difference from corresponding training session metric.

Figures 17 and 18 display differences in individual acceleration-speed profiles in-situ computed using GPS data from the training session and competitive game for one player.

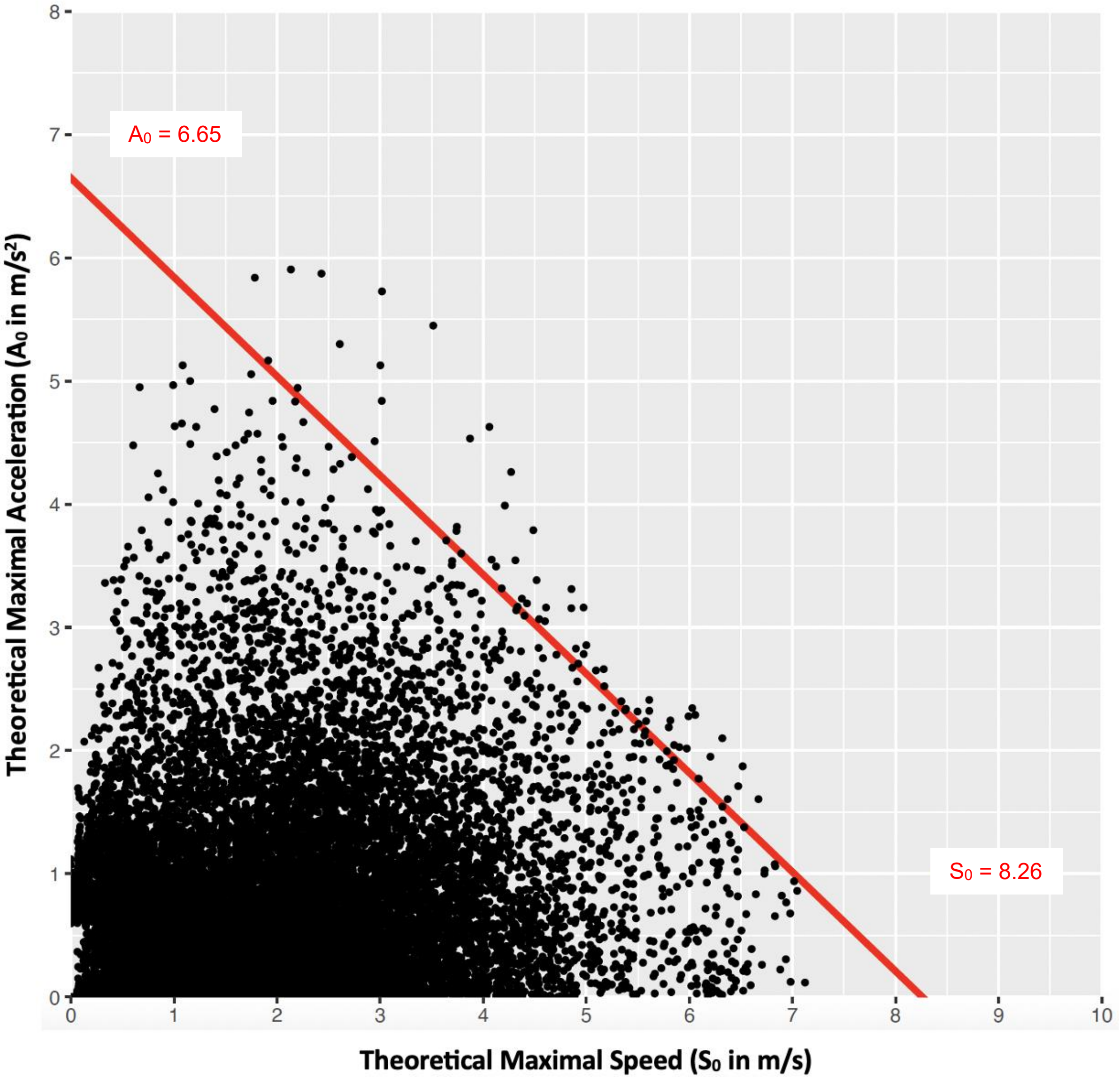

Figure 17: Individual acceleration-speed profile in-situ obtained from the GPS data of the training session for one example player. Theoretical maximal acceleration (A_0 = 6.65 m/s^2) and speed (S_0 = 8.26 m/s).

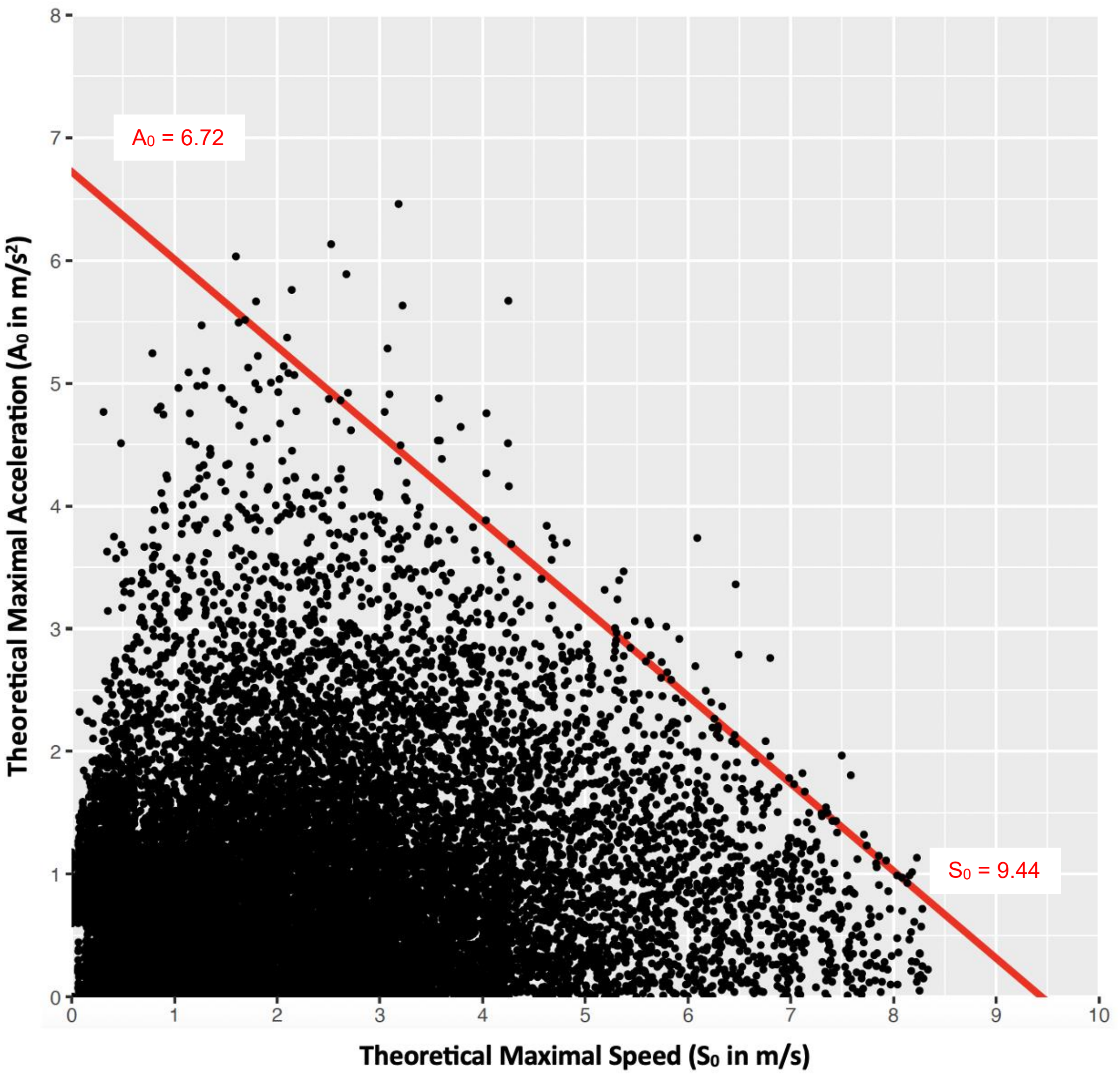

Figure 18: Individual acceleration-speed profile in-situ obtained from the GPS data of the competitive game for one example player. Theoretical maximal acceleration (A_0 = 6.72 m/s^2) and speed (S_0 = 9.44 m/s).

5.8 Study 3 – GPS force-velocity profiling (30-m maximal sprint testing) vs GPS acceleration-speed profiling (training session in-situ)

There were no significant differences in F_0 and A_0, or V_{max} and S_0, between the 30-m maximal sprint testing protocol (GPS force-velocity profiling) and training session (GPS acceleration-speed profiling in-situ) ($p > 0.05$). Figure 19 demonstrates the level of agreement in mean F_0 and A_0, or V_{max} and S_0, between the 30-m maximal sprint testing protocol and training session.

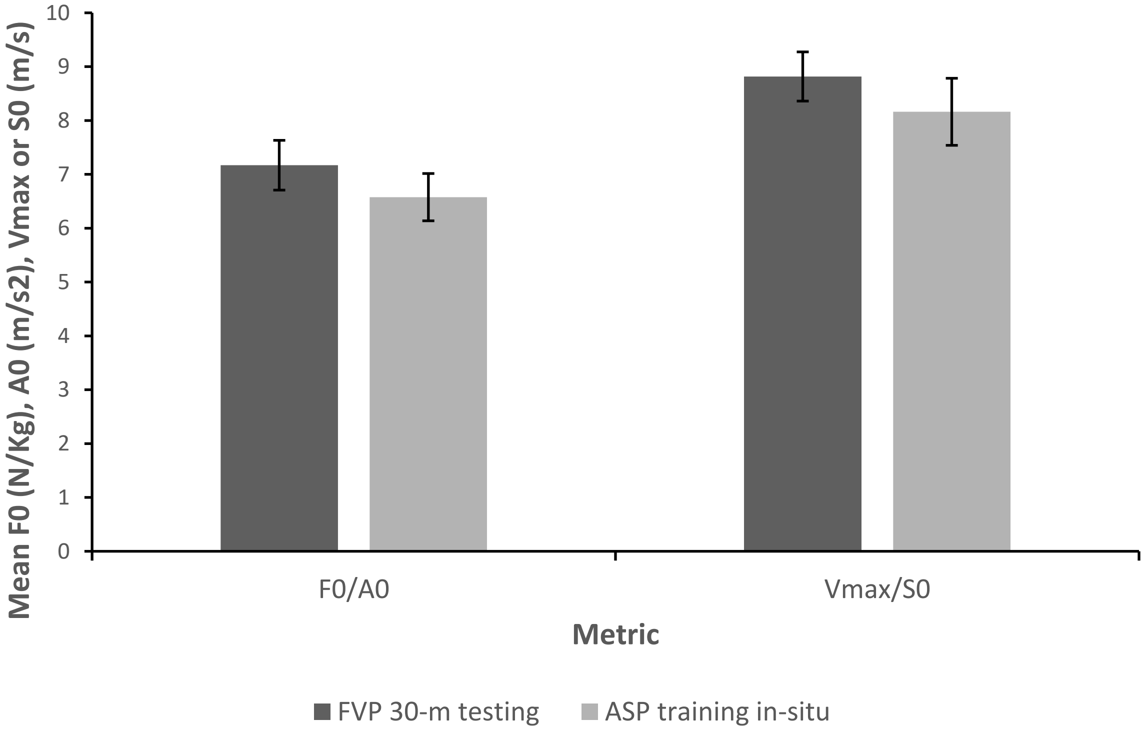

Figure 19: F_0 and A_0, or V_{max} and S_0, between the 30-m maximal sprint testing protocol and training session. Data presented as means with error bars denoting SD.

Figures 20 and 21 display differences in the force-velocity profile (30-m maximal sprint testing protocol) and acceleration-speed profile (training session in-situ) for the same player.

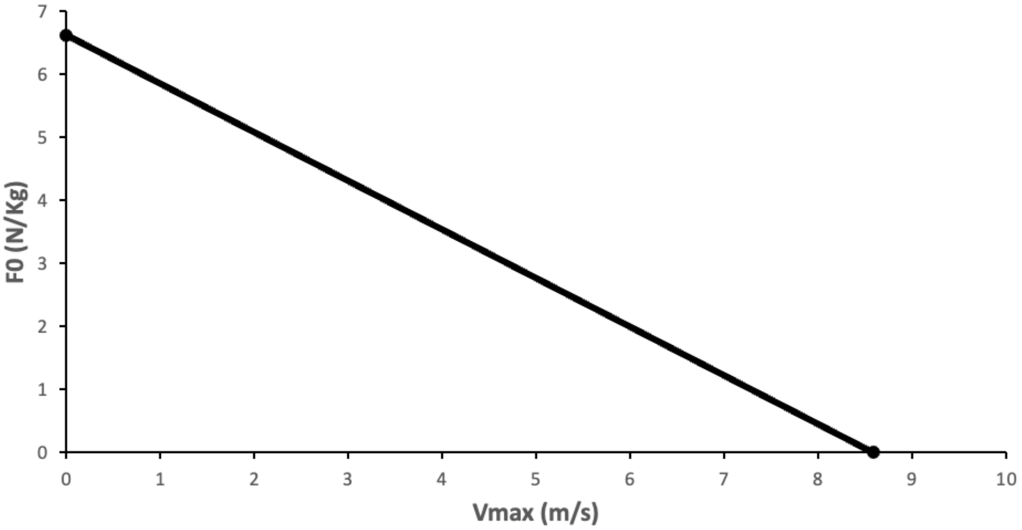

Figure 20: Force-velocity profile computed from the 30-m maximal sprint testing GPS data. Theoretical maximal horizontal force (F_0 = 6.61 N/Kg) and velocity (V_{max} = 8.59 m/s).

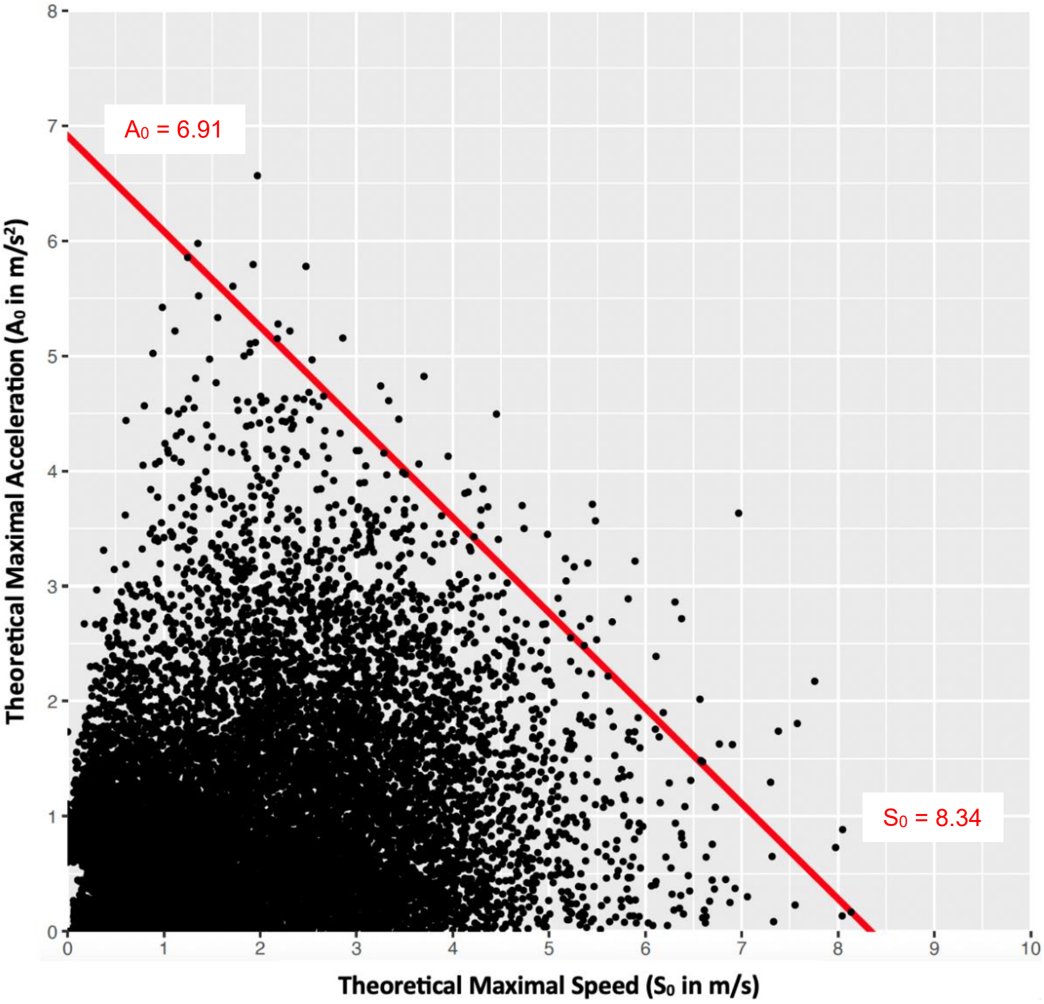

Figure 21: Acceleration-speed profile in-situ derived from training session GPS data. Theoretical maximal acceleration (A_0 = 6.91 m/s^2) and speed (S_0 = 8.34 m/s).

5.9 Study 4 – Prospective HMI risk – acceleration-speed profiling risk quadrants

During the competitive game (figure 23) there is a shift towards higher S_0 relative to the squad average with A_0 remaining fairly consistent, and more players display significant deviation from the squad average for both A_0 and S_0 when compared to the training session (figure 22).

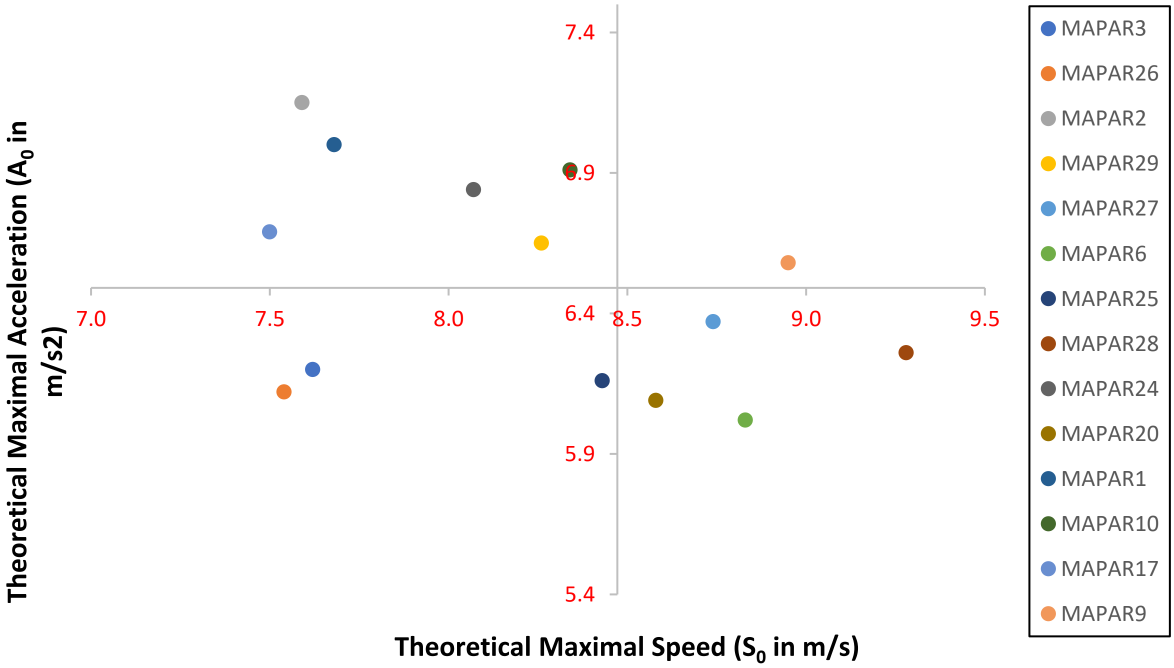

Figure 22: Quadrant chart displaying acceleration-speed profile in-situ variables (A_0 and S_0) for each player during the training session. Axis crossover determined by squad averages.

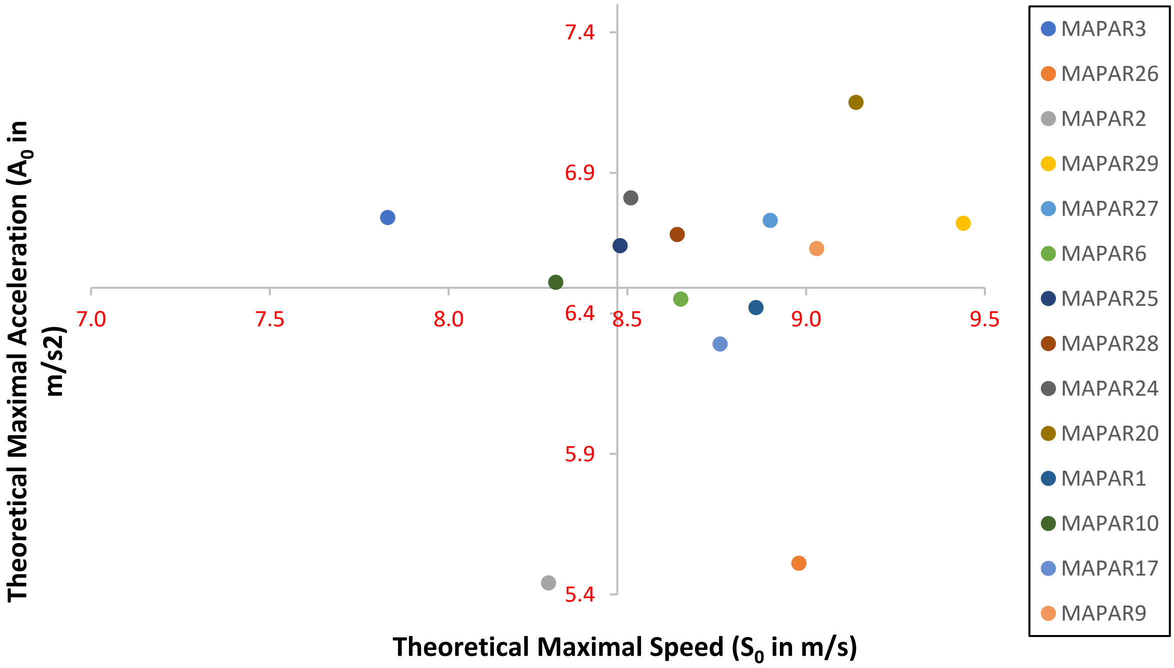

Figure 23: Quadrant chart displaying acceleration-speed profile in-situ variables (A_0 and S_0) for each player during the competitive game. Axis crossover determined by squad averages.

6.0 Discussion

The aim of the project was to investigate force-velocity and acceleration-speed profiles in elite football, including an examination of the validity and reliability of current profiling techniques, to provide insight into elite footballers' sprint mechanical capabilities and anecdotal evidence pertaining to prospective HMI risk within this population. Study 1 reported high intra and inter-tester reliability when using the MySprint app to derive force-velocity profiles from 30-m maximal sprint testing and provides the most valid and reliable force-velocity profiling technique (GPS). Study 2 demonstrated distance-induced variation in force-velocity profiles derived from 30 and 40-m maximal sprints. Study 3 highlights differences in acceleration-speed profiles between training and competitive games, proposing that ~45 minutes of training data (MD-4) is adequate to provide acceleration-speed profiles in-situ which closely resemble force-velocity profiles from maximal sprint testing meaning practitioners can use acceleration-speed profiling in-situ interchangeably with force-velocity profiling. Study 4 elucidates that acceleration-speed profiling in-situ can be used to indicate higher potential prospective hamstring muscle injury risk during competitive games in the elite football environment.

6.1 Descriptive data

The descriptive data outlined in table 5 aligns with normative data obtained from previous research. F_0 is within the range of 6.66 – 9 N/Kg (Jiménez-Reyes et al., 2018: Haugen et al., 2020). V_{max} is within the standard deviation overlap of 8.91 ± 0.23 m/s (Baumgart et al., 2018). The MySprint app is the only exception, deviating from normative data for both F_0 and V_{max}. A_0 and S_0 are within the ranges of 5.14 – 9.22 m/s^2 and 6.23 – 12.09 m/s (Morin et al., 2021: Alonso-Callejo et al., 2022: López-Sagarra et al., 2022: Clavel et al., 2023).

6.2 Study 1 – Intra-tester reliability

There was no significant difference in F_0 or V_{max} when the MySprint analysis procedure was repeated by the same tester for the 30-m maximal sprint testing protocol. RMSE and CV values for F_0 and V_{max} were both interpreted as 'good' (RMSE < 0.2, CV < 10%), indicating high levels of accuracy and low dispersion of measurements. ICC demonstrated good and excellent levels of agreement in the values of F_0 and V_{max}. Excellent intra-tester reliability means a single tester is capable of using the MySprint app to reliably calculate sprint mechanical variables from 30-m maximal sprint testing protocols, facilitating the use of the MySprint app for split time calculation for the 40-m maximal sprint testing protocol. This aligns with work investigating intra-tester reliability of the MySprint app for sprint split time calculation and thus resultant mechanical variable computation from 30-m maximal sprint testing, reporting similar good-to-excellent levels of agreement within experienced (ICC = 0.984) and non-experienced (ICC = 0.862) testers (Mildenberger et al., 2024), alongside low dispersion of measurements (CV = 1.307%), reporting high test-retest reliability (Thapa et al., 2023). The lower level of intra-tester agreement in F_0 (ICC = 0.832) compared to V_{max} (ICC = 0.976) (figure 7) might be explained by subjectivity of manual frame selection using the MySprint app inducing changes in sprint split time calculation, leading to F_0 variation if the visual inspection of the moment at which body movement started was identified incorrectly (Morin., 2017).

There were significant differences in F_0 and V_{max}, with medium to large effect sizes reported, when the MySprint app and spreadsheet analysis procedure was repeated by the same tester for the 40-m maximal sprint testing protocol. RMSE and CV values for F_0 and V_{max} were interpreted as 'poor-to-moderate' (RMSE > 0.2) and 'good' (CV < 10%), indicating lower levels of accuracy but low dispersion of measurements. ICC demonstrated good and poor levels of agreement in the values of F_0 and V_{max}. Moderate intra-tester reliability means a single tester is capable of using the MySprint app and spreadsheet analysis procedure to reliably calculate sprint mechanical variables from 40-m maximal sprint testing protocols. However, this combined analysis procedure displays lower accuracy in the computation of F_0 and V_{max}, and lower levels of agreement in V_{max} (figure 8) when compared to the MySprint app analysis of 30-m maximal sprint testing (figure 7). This may be due to data manipulation or transfer errors when manually inputting sprint split times calculated by the MySprint app into the force-velocity profile spreadsheet, in order to derive the relevant sprint mechanical variables from the 40-m maximal sprints. Multi-stage integrative index calculation i.e., sprint mechanical variables derived from a combination of the MySprint app and force-velocity profile spreadsheet, can magnify measurement inaccuracies, reducing intra-tester reliability (Samozino et al., 2022a). In short, practitioners should use one of either the MySprint app or calculation spreadsheet for 30-m sprint testing, but should not use the combination of the MySprint app and calculation spreadsheet for 40-m sprint testing, to reduce potential intra-tester error induced by the latter.

6.3 Study 1 – Reliability and validity of MySprint app against calculation spreadsheet

There was no significant difference in F_0 or V_{max} between the MySprint app and the calculation spreadsheet analysis procedures for the 30-m maximal sprint testing protocol. RMSE and CV values for F_0 and V_{max} were all interpreted as 'good' (RMSE < 0.2, CV < 10%), indicating high levels of accuracy and low dispersion of measurements. ICC demonstrated excellent levels of agreement in the values of F_0 and V_{max} between procedures. Spearman's rank correlation coefficient revealed significant very strong associations in F_0 and V_{max} between the MySprint app and the calculation spreadsheet (figure 9), purporting concurrent validity as demonstrated by the scatter plots and correlation matrix' with low standard error of measurements. Excellent inter-method reliability and validity means the MySprint app and force-velocity spreadsheet can be used interchangeably to calculate sprint mechanical variables from 30-m maximal sprint testing protocols. The force-velocity spreadsheet can be employed to calculate sprint mechanical variables for the 40-m maximal sprint testing protocol, using sprint split times generated by the MySprint app. Any differences in sprint mechanical variables output between the 30-m (MySprint app) and 40-m (MySprint app and calculation spreadsheet) maximal sprint testing protocols are likely due to data manipulation and transfer errors or biological variation. The two methods display excellent reliability, validity, and agreement, to be expected as the underlying biomechanical models integrated to calculate sprint mechanical variables are identical – based on the ‘simple method’ of force-velocity profiling, previously validated against the historical ‘gold standard’ force plate systems (Samozino et al., 2016: Morin et al., 2019).

6.4 Study 1 – Inter-tester reliability

There was no significant difference in F_0 or V_{max} between the two testers performing the MySprint app analysis procedure for the 30-m maximal sprint testing protocol. RMSE and CV values for F_0 and V_{max} were all interpreted as ‘good’ (RMSE < 0.2, CV < 10%), indicating high levels of accuracy and low dispersion of measurements. ICC demonstrated excellent levels of agreement in the values of F_0 and V_{max} between the two testers. Excellent inter-tester reliability means the MySprint app can be used by different testers interchangeably to calculate sprint mechanical variables from 30-m maximal sprint testing protocols. Bland-Altman limits of agreement (±1.96 SD) were ±0.03 N/Kg and ±0.008 m/s, for F_0 and V_{max} respectively, with the majority of points close to 0 and consistent variability throughout the force or velocity continuum thus indicating the absence of proportional bias (figure 10). Previous studies investigating inter-observer sprint split time calculation using the MySprint app for both 30 and 40-m maximal sprint testing concur, reporting excellent inter-tester reliability (ICC = 0.969 – 1) (Romero-Franco et al., 2017: Mildenberger et al., 2024: Thapa et al., 2023). This closely reflects the level of agreement in the current study (ICC = 0.986 – 0.988), but despite continuity in results, observer experience was unclear in two out of the three comparison studies which could potentially lead to disparities in sprint split time calculation and resultant mechanical variables between testers possessing different levels of MySprint app competence. In synthesis, different testers can use the MySprint app for force-velocity profiling of 30-m sprints, aiding accessibility, particularly crucial in the time-constrained elite football environment.

6.5 Study 1 – Validity and inter-trial reliability (30-m maximal sprint testing protocol)

6.5.1 Validity of the MySprint app and GPS against 'gold standard' radar device

There were significant differences in F_0, V_{max}, and FV_{slope} computed by the MySprint app, radar, and GPS units with large effect sizes reported. Pairwise comparisons reported significant differences in F_0 and V_{max} between the MySprint app and radar device ($p < 0.05$, figure 11) and force-velocity profiles visualised differences in the FV_{slope} between the MySprint app, radar, and GPS units (figure 12), in conjunction with research identifying low agreement in sprint split times and resultant mechanical variables calculated between the MySprint app and other instruments (Mildenberger et al., 2024: Thapa et al., 2023). Another study contrasts our results, finding high levels of agreement in sprint mechanical variables between the MySprint app and radar (Romero-Franco et al., 2017). Divergence in levels of agreement in sprint mechanical variables between the MySprint app and radar device in the current study is most likely due to the MySprint app's high sensitivity to negligible changes in sprint start time determination, potentially leading to F_0 over-inflation and V_{max} reduction if the visual inspection of the moment at which body movement started was identified incorrectly (Morin., 2017).

However, there were no significant differences in F_0 or V_{max} ($p > 0.05$) between the GPS and radar device, aligning with previous studies revealing moderate-to-perfect correlations between radar and GPS-derived force-velocity variables, with large error bias subsequently reduced when GPS units with higher sampling rates (≥10Hz) were utilised (Clavel et al., 2022: Nagahara et al., 2017). Bland-Altman limits of agreement (±1.96 SD) between the GPS and radar device were ±0.194 N/Kg and ±0.09 m/s, for F_0 and V_{max} respectively, with the majority of points close to 0 and consistent variability throughout the force or velocity continuum thus indicating the absence of proportional bias (figure 13). Caution is warranted when comparing the results of these studies as different GPS hardware exhibits varying degrees of validity against radar devices in the measurement of sprint mechanical variables derived from maximal sprint testing. Exploring this premise, the GPS units manufactured by STATSports used in the current study demonstrated moderate-to-good validity whereas the Catapult alternative provided good validity across all metrics (Cormier et al., 2023c). Overall, GPS is the most valid against the 'gold standard' radar device for 30-m sprint testing. However, the practitioner needs to be clear on the type of GPS they're using as validity can vary between different device manufacturers and specific models.

6.5.2 Inter-trial reliability – Within equipment between two sprints performed

There were no significant differences in F_0 or V_{max} ($p > 0.05$) between the two sprints performed by each player for all equipment types used (MySprint/Radar/GPS), indicating that all equipment types were reliable in the measurement of sprint mechanical variables between sprint repeats (figure 14). For F_0 and V_{max} between the two sprints performed by each player, ICC reported poor and good levels of agreement for the MySprint app, poor and moderate levels of agreement for the radar device, and poor levels of agreement for the GPS. RMSE and CV values for the MySprint app derived F_0 and V_{max} were interpreted as 'poor' (RMSE > 0.2) and 'good' (CV < 10%). Values for the radar device computed F_0 and V_{max} were interpreted as 'poor' (RMSE > 0.2) and 'good' (CV < 10%). Outputs for the GPS F_0 and V_{max} were interpreted as 'poor' (RMSE > 0.2) and 'good' (CV < 10%). This reflects previous research investigating the inter-trial reliability of the MySprint app, reporting limited variation in sprint mechanical variables between sprint repeats (CV = 0.14%) (Romero-Franco et al., 2017). Studies examining the inter-trial reliability of radar devices have identified larger variation and slightly lower agreement in sprint mechanical variables between sprint repeats (CV = 1.4 – 11%, ICC = 0.75 – 0.99), although these can still be interpreted as demonstrating good reliability (Simperingham et al., 2019: Edwards et al., 2022). Other work has identified similar reliability of GPS in the measurement of sprint mechanical variables between sprint repeats (CV = 0.1 – 11.53%) (Vantieghem-Nicolas et al., 2023: Fornasier-Santos et al., 2022). These studies reinforce the findings of the current study, demonstrating similar levels of reliability in the radar device and GPS derived sprint mechanical variables between sprint repeats.

The current study highlights increased reliability and level of agreement in V_{max} compared to F_0, within all equipment types between sprint repeats. This trend is supported by all the aforementioned force-velocity profiling studies, reporting increased reliability when measuring sprint mechanical variables related to speed – towards the velocity side of the spectrum, as opposed to lower reliability for force-dependent variables. Research investigating the reliability of acceleration-speed profiling techniques has identified the same phenomena, albeit concerning the relationship between acceleration and velocity (Alonso-Callejo et al., 2024). This may be due to each equipment type proving more inconsistent in the measurement of high levels of force towards the start of sprint accelerations, compared to maximal velocity measurement. In practical terms, the GPS unit demonstrates 0.69 N/Kg and 0.23 m/s variability in F_0 and V_{max} respectively, between sprint repeats, falling adequately below the 1 N/Kg decrease of F_0 associated with 2.67 times higher risk of sustaining a new hamstring injury (Edouard et al., 2021). These results warrant caution as the combined effect of several levels of error i.e., biological, intra-tester, and equipment, means it is difficult to definitively attribute the reasons for particular divergence in sprint mechanical variables between trials.

6.6 Study 2 – Distance-induced variation in force-velocity profiles

There were significant differences in sprint mechanical variables derived from the GPS unit between the two sprint distances (30 and 40-m), with large effect sizes reported. The longer sprint distance resulted in reduced F_0 and FV_{slope}, but higher V_{max} when compared to the shorter sprint distance (figure 15). This aligns with previous research investigating sprint mechanical variables in elite football players, reporting stronger correlations between F_0 and sprint performance, and weaker correlations between V_{max} and sprint performance, during shorter distance sprints. This is accompanied by a velocity orientated shift in the force-velocity profile with increasing sprint distance, concomitant with reductions in observed FV_{slope} values (Haugen et al., 2019: Baumgart et al., 2018: Altmann et al., 2015: Baena-Raya et al., 2022). These findings can be explained by the optimal force-velocity profile and underlying sprint mechanical variables i.e., F_0 and V_{max}, being highly dependent on sprint distance, with shorter sprint distances associated with a profile oriented towards maximal horizontal force and longer sprint distances associated with a profile oriented towards maximal running velocity (Samozino et al., 2022b). Another influencing factor may be varying effort of the players throughout the different stages of the sprint between sprint distances, perhaps displaying reduced initial maximal force application during the longer distance sprint in order to conserve energy for the entire sprint duration, as opposed to 'all-out' initial maximal force application during the shorter distance sprint. FV_{slope} reductions with increasing sprint distance likely occurred as players were required to accelerate over a longer distance rather than just applying maximal force in the initial acceleration phase (Haugen et al., 2019), and higher maximal running velocity was reached after 30-m (Buchheit et al., 2012). Therefore, the distance selected for sprint testing should be dependent on the targeted testing outcome i.e., 30-m for maximal horizontal force, or 40-m for maximal running velocity assessment.

6.7 Study 3 – Acceleration-speed profiles in-situ (training vs. competitive games)

The S_0 was significantly higher in the competitive game compared to training (8.7 ± 0.4 m/s vs. 8.24 ± 0.59 m/s), with medium effect size reported, but there were no significant differences in A_0 or AS_{slope} ($p > 0.05$, figure 16). In agreement with these results, one study reported increased S_0, but in contrast to the current study, highlighted higher A_0 and more negative AS_{slope} during a competitive game compared to a training session (MD-4) (Alonso-Callejo et al., 2022). These contradicting findings may be explained by the other study failing to adequately incorporate maximal sprint acceleration and velocity exposure into the training session consequently reducing the values of A_0 and S_0 (Clavel et al., 2023), although this is difficult to determine as the specific components of the training session were unclear. Several studies have declared no significant differences in A_0 or S_0 between cumulated training data

(~5 sessions) and a competitive game (Alonso-Callejo et al., 2024: Clavel et al., 2023). A_0 was consistent between the training sessions and competitive game, in conjunction with the results of the current study, perhaps as training programme prescription incorporated similar medium-sided games (6 vs. 6 – 8 vs. 8 + 2 GKs) which encourage maximal acceleration exposure as reducing the number of players per side increases acceleration demands (Silva et al., 2023). S_0 was also consistent between the training sessions and competitive game, contrasting the results of the current study, likely due to the cumulated training session data including MD+1 'top-ups' meaning players who played < 60 minutes during the competitive game used this day to achieve high-speed running demands (Alonso-Callejo et al., 2024). The other study incorporated 'physical conditioning' components including maximal sprints, alongside large-sided games (up to 9 vs. 9 + 2 GKs) within the cumulated training session data (Clavel et al., 2023). These training session prescriptions likely acted to enhance maximal velocity exposure through sprinting (Buchheit et al., 2023) and increased pitch size (Clavel et al., 2023), resulting in increased S_0 which closely represents the same values derived from the competitive game.

The divergence in S_0 between training and competitive games can potentially be further explained by a lack of ecological validity including adequate competitive stimuli in training which during match-play, act to stimulate maximal performance in sprinting tasks (Caldbeck, 2019). Additional variation in training and match load resulting in alterations in acceleration-speed profile variables can be induced by a multitude of factors: weekly schedule, age group, training mode (Teixeira et al., 2021), contextual factors i.e., level of opposition (Martin-Garcia et al., 2019), tactical formation (Calder & Gabbett., 2022), and individual playing style (Trewin et al., 2017). All of these components may contribute to alterations in the spread of acceleration-speed points and altering the percentage of maximum speed (>95%) reached, thus changing profiles between training and competitive games (Clavel et al., 2023). The main difference in the acceleration-speed profiles in-situ between the training session (figure 17) and competitive game (figure 18) is the reduced number of acceleration-speed points towards the higher velocity spectrum visible on the training session profile. This translates into a lower proportion of instances where a higher percentage of maximum speed was reached, leading to reduced S_0. The number of acceleration-speed points towards the lower velocity spectrum is similar during both the training session and competitive game, resulting in comparable A_0.

6.8 Study 3 – Force-velocity profiling vs acceleration-speed profiling in-situ

There were no significant differences in F_0 and A_0, or V_{max} and S_0, between the 30-m maximal sprint testing protocol (GPS force-velocity profiling) and training session (GPS acceleration-speed profiling in-situ) ($p > 0.05$, figure 19). Figures 20 and 21 visually demonstrate similarities between the force-velocity and acceleration-speed profile for the same player, highlighting continuity in relevant sprint mechanical variables (F_0 and A_0, V_{max} and S_0). This is supported by research concluding that acceleration-speed profiles in-situ generated from cumulated training and match data are comparable to force-velocity profiles derived from maximal sprint testing (Cormier et al., 2023b). However, it should be noted that this study aggregated 15-19 training sessions and competitive games GPS data to provide the acceleration-speed profile in-situ rather than a single training session, utilised 40-m maximal sprint testing, and incorporated elite female footballers, which distinguishes it from the current study's findings. Examining this premise, one previous study has also investigated force-velocity profiles from 30-m maximal sprint testing against acceleration-speed profiles in-situ derived from a 45-minute training session, similarly reporting no significant difference in V_{max} and S_0 with low absolute bias, but variation in F_0 and A_0 with moderate absolute bias (Komino, 2022). The deviation concerning F_0 and A_0 contrasts the current study, perhaps due to the sample demographic which consisted of recreational youth football players who likely have reduced capacity to generate acceleration throughout the velocity spectrum during the training session in-situ when compared to elite youth football players. Also, the MD-4 training session used for GPS in-situ data acquisition in the current study was intentionally selected as players typically exhibit the highest training load, including maximal acceleration and velocity values, most closely reflecting those obtained during competitive games (Stevens et al., 2017). This likely induced less variation in F_0 and A_0 between the 30-m maximal sprint testing protocol and training session. However, the aforementioned study incorporated an unquantified intensity 45-minute soccer period resulting in low cloud density of the acceleration-speed profile in-situ which did not include maximal acceleration points at all possible running speeds due to a lack of high intensity actions during the monitoring period, leading to greater deviation in F_0 and A_0 between the 30-m testing protocol and training session (Morin et al., 2021: Clavel et al., 2023).

A more recent study has compared the force-velocity profile derived from GPS data of maximal sprint testing against the acceleration-speed profiles in situ computed from cumulated GPS data of five training sessions and a match (ASP1) and five training sessions (ASP2). ASP1 demonstrated the highest agreement with the force-velocity profile, whereas ASP2 showed lower agreement in almost all sprint mechanical variables (Alonso-Callejo et al., 2024). The main reason for disparities in F_0 and A_0, or V_{max} and S_0 between this study and the current study is the incorporation of five training sessions in ASP2 (MD-4, MD-3, MD-2, MD-1, MD+1). The training sessions on MD-3, MD-2, and MD-1 are typically associated with lower training load, thus reduced maximal acceleration and velocity values than MD-4, which diverge further from sprint mechanical variable values obtained during sprint testing (Akenhead et al., 2016).

An important consideration is the minimum amount of GPS data required to provide valid and reliable acceleration-speed profiles in-situ, to facilitate comparison between force-velocity and acceleration-speed profiles in-situ. However, different studies have reported contrasting observations: >45-90 minutes of training or competitive game data (Morin et al., 2021), 5 to 9 days of tracking data (Alonso-Callejo et al., 2024: Cormier et al., 2023a), and ~45 minutes of in-situ method data (Komino, 2022). The current study demonstrates that acceleration-speed profiles in-situ deriving from GPS data of a training session conducted on MD-4 comprising of a medium-sided game lasting 45-minutes (8 vs. 8 + 2 GKs) displays high agreement with force-velocity profiles (and sprint mechanical variables) derived from 30-m maximal sprint testing. Therefore, it can be proposed that ~45 minutes of training data (MD-4) provides acceleration-speed profiles in-situ which closely resemble maximal force-velocity profiles, questioning the need for isolated sprint testing (Cormier et al., 2023b: Morin et al., 2021).

6.9 Study 4 – Prospective HMI risk – acceleration-speed profiling risk quadrants

For most players, during the competitive game (figure 23) there is a shift towards higher S_0 relative to the squad average with A_0 remaining fairly consistent, and more players display significant deviation from the squad average (centre of the quadrant chart) for both A_0 and S_0 when compared to the training session (figure 22). Consistent A_0 combined with increased S_0 during the competitive game compared with the training session invokes greater imbalance in the acceleration-speed relationship, perhaps indicating increased risk of sustaining hamstring muscle injury during competitive games. This aligns with previous research reporting higher risk of sustaining HMI during competitive games (Woods et al., 2004) and following imbalances in the force-velocity or acceleration-speed profiles (Edouard et al., 2021: Edouard et al., 2024: Clavel et al., 2023). However, acceleration-speed profiles vary between different training micro-cycle session days (Alonso-Callejo et al., 2022) and competitive games (Lopez-Sagarra et al., 2022), potentially regulating HMI risk 'flags' when different training sessions and competitive games are compared. Using an individual player as an example to 'flag', MAPAR26 can be seen moving from the low acceleration, low speed quadrant during training, to the low acceleration, high speed quadrant during the competitive game. This demonstrates a shift towards the higher velocity spectrum, resulting in increased imbalance between A_0 and S_0, and further deviation away from the squad norm, potentially heightening the risk of sustaining HMI (figure 4). This player should be actively attempting to reach maximal velocity during training and improve their maximal velocity capacity, through coach encouragement, specific drill design, and individual training prescription to prevent imbalance and protect against potential HMI (Buchheit et al., 2023: Edouard et al., 2023: Prince et al., 2021: Thorborg et al., 2020: Edouard et al., 2019: Malone et al., 2017b). Acceleration-speed profiling in-situ ‘flags’ are based on prospective HMI risk largely originating from anecdotal evidence which needs to be supported by longitudinal studies linking acceleration-speed profiling in-situ with retrospective HMI and prospective HMI risk, specifically amongst the elite football population.

6.10 Limitations

Sample sizes varied between the different hypotheses’ being examined (range: 6 – 25 players involved in relevant comparisons), due to the implicit constraints of the elite football environment limiting access to the players, alongside selecting the testing protocols, training sessions, and competitive games in which the most players participated in all components to enable further cross-comparison. Raw data constituents of relevant force-velocity profiles and acceleration-speed profiles in-situ were visually checked for anomalies i.e., clear issues with GPS data recording displayed using Microsoft Excel scatter plots with smooth lines and markers, whilst further reliability and validity measures including model RMSE were implemented, leading to additional player data exclusion. This justifies the small sample of 6 players included in the comparison between the acceleration-speed profile in-situ and the force-velocity profile from the 30-m testing protocol, both monitored using GPS during the training session (MD-4). Smaller sample sizes can potentially lead to effect size over inflation, a caveat of most research conducted in elite football environments (Schäfer & Schwarz, 2019).

Acceleration-speed profiles in-situ are dependent upon maximal forward acceleration across the entire range of the running velocity spectrum. However, the potential poor reliability of GPS units in measuring acceleration at low velocity coupled with a lack of high-speed data points may lead to unreliable acceleration-speed profiles in-situ being generated. This could be exacerbated during the training session consisting of a medium-sided game (8 vs. 8 + 2 GKs), where players likely achieve fewer high-speed data points due to drill design and pitch dimensions. For both the training session and competitive game there is an overall reduction in the number of acceleration-speed points throughout the velocity spectrum when considering the minimal duration monitored (45-minute training session, >45-minutes competitive game), potentially leading to less reliable acceleration-speed profiles in-situ. In the current study, individuals were included in further acceleration-speed profile in-situ analysis if they had participated in a minimum of 45-minutes during the training session, 45-minutes in their respective competitive game, and reached > 95% of peak speed (from individualised GPS software thresholds based on cumulated historical training/game data) in both instances.

Incorporating a single training session and competitive game may not have been enough to reliably assess prospective HMI risk due to the high amount of variability in acceleration-speed profiles in-situ between different training micro-cycle session days and competitive games. The inclusion of more training sessions and competitive games is required to adequately assess variability in relevant profiles and determine the potential prospective HMI risk.

6.11 Conclusion

6.11.1 Study 1 – Validity and reliability of force-velocity profiling techniques

There was adequate intra-tester reliability from the 30-m (MySprint app), but not from the 40-m maximal sprint testing protocol (MySprint/Spreadsheet). The MySprint app demonstrated high levels of reliability and validity against the calculation spreadsheet. There was excellent inter-tester reliability when using the MySprint app for 30-m maximal sprint testing. GPS was valid whereas the MySprint app was not valid against the ‘gold standard’ radar device when determining force-velocity profiles and sprint mechanical variables from 30-m maximal sprint testing. All equipment (radar device, MySprint app, and GPS unit) demonstrated similar levels of moderate inter-trial reliability in the measurement of sprint mechanical variables between sprint repeats, with GPS displaying values most closely representing the radar device. Overall, GPS appeared to be the most valid and reliable force-velocity profiling technique.

6.11.2 Study 2 – Distance-induced variation in force-velocity profiles

Different sprint distances induced variation in force-velocity profiles, with the longer sprint distance resulting in reduced F_0 and FV_{slope}, but higher V_{max}, when compared to the shorter sprint distance, suggesting that 30-m sprint testing should be used for maximal horizontal force and 40-m for maximal running velocity assessment.

6.11.3 Study 3 – Acceleration-speed profiling in-situ

Acceleration-speed profiles in-situ differed, demonstrating increased S_0 with no change in A_0 during the competitive game when compared to the training session. Profiling variables were consistent between the 30-m maximal sprint testing protocol (GPS force-velocity profiling) and training session in-situ (GPS acceleration-speed profiling). Therefore, it is proposed that~45 minutes of training data (MD-4) is adequate to provide acceleration-speed profiles in-situ which closely resemble force-velocity profiles from maximal sprint testing.

6.11.4 Study 4 – Acceleration-speed profiling in-situ and potential prospective HMI risk

There was a shift towards higher S_0 relative to the squad average with A_0 remaining consistent, and more players displayed significant deviation from the squad average (centre of the quadrant chart) for both A_0 and S_0 when compared to the training session, potentially indicating increased HMI risk during the competitive game. Practitioners can use acceleration-speed profiling in-situ interchangeably with force-velocity profiling, possibly shifting away from time-consuming maximal sprint testing protocols, perhaps to indicate higher potential prospective hamstring muscle injury risk during competitive games.

6.12 Practical applications

- Practitioners should use one of either the MySprint app or calculation spreadsheet for 30-m sprint testing, but should not use the combination of the MySprint app and calculation spreadsheet for 40-m sprint testing, to reduce potential intra-tester error.
- Different testers (members of staff at football club) can use the MySprint app for force-velocity profiling of 30-m sprints which aids accessibility when no advanced training is required, proving particularly crucial in the time-constrained elite football environment.
- GPS is the most valid against the ‘gold standard’ radar device for 30-m sprint testing and is accessible compared to expensive radar devices with tedious setup. However, the practitioner needs to be clear on the type of GPS they’re using as validity can vary between different device manufacturers and specific models.
- The GPS should be used for between-sprint comparisons as it closely matches the radar device and demonstrates 0.69 N/Kg and 0.23 m/s inter-trial variability in F_0 and V_{max} respectively, falling adequately below the 1 N/Kg decrease of F_0 associated with 2.67 times higher risk of sustaining a new hamstring injury (Edouard et al., 2021).
- The specific distance selected for maximal sprint testing should be dependent on the targeted testing outcomes i.e., use 30-m for maximal horizontal force assessment, or 40-m for maximal running velocity assessment.
- ~45 minutes of training data (MD-4) is adequate to provide acceleration-speed profiles in-situ which closely resemble maximal force-velocity profiles, questioning the need for isolated sprint testing, meaning the practitioner can ‘test players without testing them’.
- Players should be actively attempting to reach maximal velocity during training, and improve their maximal velocity capacity through coach encouragement, specific drill design, and individual training prescription to prevent imbalance between training sessions and competitive games, protecting against potential prospective HMI.

6.13 Future directions of research

Studies should aim to include larger more representative samples of sufficient size to provide adequate power necessary to derive more reliable and statistically sound conclusions, further acting to increase the generalisability of findings to the elite footballer population. Working on this premise, the current study demonstrated that acceleration-speed profiles in-situ deriving from GPS data of a training session conducted on MD-4 comprising of a medium-sided game lasting 45-minutes (8 vs. 8 + 2 GKs) displayed high agreement with force-velocity profiles (and sprint mechanical variables) derived from 30-m maximal sprint testing. Therefore, it can be proposed that ~45 minutes of training data (MD-4) provides acceleration-speed profiles in-situ which closely resemble maximal force-velocity profiles. However, the sample size for this element of the study was only 6 players, meaning future investigations should aim to corroborate or contrast these findings using larger samples. Also, the potential influence of micro-cycle session days i.e., MD-4 vs. MD-2, should be sufficiently considered as training session content can influence GPS data for acceleration-speed profiles in-situ computation.

An interesting avenue of research involves the longitudinal assessment of acceleration-speed profiles in-situ over the course of an entire season. Incorporating more training sessions and competitive games will provide more reliable assessment of retrospective and prospective HMI risk due to the high amount of variability in acceleration-speed profiles in-situ between different training micro-cycle session days and competitive games. Future studies could compare the reliability and validity of GPS units manufactured by different companies in determining acceleration-speed profiles in-situ. To mitigate against the potential poor reliability of GPS units in measuring acceleration at low velocity coupled with fewer high-speed data points, the acceleration-speed profiles could be weighted to higher velocity using regression, or the maximal velocity value from sprint testing. Furthermore, an intervention study based on the implementation of different preventative HMI strategies could be conducted, seeking to move players around the quadrant charts from areas of higher to lower potential HMI risk.

Resources

Spreadsheet to determine force-velocity profiles from sprint split times (40m)

file:///Users/robertstockdale/Library/CloudStorage/OneDrive-LancasterUniversity/Masters/DATA/Force-Velocity Spreadsheet.xlsx

Spreadsheet to determine force-velocity profiles from GPS data (30 and 40m)

file:///Users/robertstockdale/Library/CloudStorage/OneDrive-LancasterUniversity/Masters/DATA/GPS F-V.xlsx

Spreadsheet to determine force-velocity profiles from radar data (30m)

file:///Users/robertstockdale/Library/CloudStorage/OneDrive-LancasterUniversity/Masters/DATA/Radar F-V.xlsx

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