Manuscript Title: A commentary on soccer match-play simulations for applied research and practice

Running Head: Soccer match simulations

Submission Type: Commentary

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Abstract: Soccer is a fast-growing area of research, demonstrated by a 10-fold increase in the number of PubMed articles derived from the search term ‘soccer’ between 2001 and 2021. The scope of contemporary soccer-related articles ranges from match-play observations to laboratory evaluations of performance. The activity profile of soccer match-play is variable and techniques to collect data within matches are limited. Soccer-specific simulations have been developed to simulate the evolving demands of match-play. The evolutionary designs of novel simulations provide a reproducible exercise stimulus for varying researcher and practitioner objectives. The applied researcher can utilise simulations to investigate the efficacy of nutritional interventions and environmental stress on performance, while assessing the physiological and biomechanical responses to representations of match-play. Practitioners can adopt simulations for rehabilitation to progressively facilitate return-to-play processes, while implementing extra top-up conditioning sessions for unused and partial-match players. However, there are complexities involved with the selection of varying simulations which are dependent on the research question or practical application. There also remains a paucity of published information to support researchers and practitioners in selecting from differing simulation models. To assist with researcher and practitioner interpretations, we present a commentary of the current simulations to inform decision-making processes for research and training purposes and enhance the application of future research. An objective scoring system was adopted for rating the research and practical applications of each simulation design. Overall scores of 22, 16 and 18 out of 36 were revealed for free-running (*n*=7), non-motorised- (*n*=4) and motorised-treadmill-based simulations (*n*=4), respectively.

Keywords: Football · field-based · free-running · treadmill · protocol

1. Introduction

During 90 min competitive soccer matches, professional male players cover 8.9—11.8 km total distance[1, 2], 0.7—3.9 km high-speed distance[3, 4], 0.2—0.6 km sprint distance[2, 5], and perform 1000—1500 locomotion changes[5-8], ~726 change-of-direction movements[9] and 50—110 technical actions.[9-11] Match-play also elicits a heart rate response of 159—175 bpm^{-1}[12, 13], blood lactate values of 2.4—10 mmol·l^{-1}[13, 14] and a mean of 70% maximal oxygen uptake ($\dot{V}O_{2max}$).[14, 15] However, soccer matches are susceptible to external factors[16, 17] and the match-to-match variability in some of these metrics is high (e.g., high-speed running).[18] Given these features, researchers face a challenging trade-off between higher external and internal validity.[15, 17] A minimum sample size of 80 (using a coefficient of variation [CV] of 20%) would be required to determine a meaningful impact of an intervention on within-match performance metrics.[16] However, recruiting such large samples of elite players for research is challenging.[19] Therefore, soccer simulation protocols have been developed to reduce the limitations outlined above when using real match-play for research. Although simulations are less ecologically valid versus a competitive soccer match, such exercise models control the movement demands and elicit repeatable physiological responses whilst attempting to simulate match-play for both research and training.[10]

Early developments in soccer simulations during the late 1990s were derived from manually computing the proportion of time spent in each movement category using video match footage of an individual player.[20] Using such methodologies to design a model that accurately simulates the demands of match-play is likely limited due to the potential inaccuracies associated with data processing and the skewed values involved with basing the simulation on an individual players' activity profile. Critical debate has occurred within the literature concerning the validation requirements of soccer simulations.[10, 19] For validation, researchers have reported the importance of a single population of players completing both the simulation and match-play with statistical comparisons being made between both exercise modes.[10, 19] The activity profile is typically validated against notational analyses of match-play, however, simulations must also be validated based on both input (distance, duration, and activity profile)[18] and output (energy requirements, heart rate, blood lactate, $\dot{V}O_2$ profiles and mechanical demands).[19] This becomes difficult considering that soccer is characterised by an intermittent and irregular activity profile, thus, increasing the complexity of both the biomechanical loading patterns and physiological response. Simulations also provide a safe and reproducible exercise stimulus that guards against physical contact, which is responsible for >70% of injuries during match-play.[21] As such, simulations are developed to safely simulate the activity profile associated with match-play for training purposes, but each designed with a specific application in mind.

Soccer simulation variants can be broadly categorised as either, free-running (also known as over ground or field-based) or treadmill-based (motorised or non-motorised). Free-running simulations closely reflect the physiological profile of match-play and possess higher ecological validity than treadmills.[22] Conversely, treadmill-based simulations elicit an analogous biomechanical fatigue response with match-play and offer increased experimental control.[18] The researcher must decide which type of simulation is most suitable for use relative to the research question posed. A study investigating change-of-direction[23] or technical aspects (e.g., dribbling skills)[24] may necessitate a free-running simulation. Whereas, a study investigating the effect of environmental stressors on physical performance and physiological responses within an environmental chamber[25, 26], should utilise a laboratory-based treadmill simulation. Primarily, the type of simulation must be considered on a continuous scale with match-play (higher ecological validity) and treadmill-based simulations (higher experimental control) at opposing ends akin to the basic-applied research continuum.[19, 27] To many researchers, simulating the demands of soccer is widely considered a reproducible alternative to match-play, although there is a lack of consensus for selecting the appropriate design in relation to the research outcomes. Therefore, given the importance of simulations and the difficulties that currently exist for researcher interpretation of the varying exercise modes for simulating match demands, summarising the key information appears warranted to improve the application of future research.

To date, two review articles exist that provide an evaluation of published research involving simulations.[10, 19] While such reviews have merit, both were published >10 years prior and there has since been a marked increase in the number of simulations developed. Accordingly, the current article provides a commentary of the simulations with a view to guiding researchers and practitioners in making informed decisions on simulation selection. Such an appraisal appears warranted to facilitate the adoption of the most suitable study designs and to highlight the varying applications of each of the simulation types within the applied setting. Considering the influx of contrasting interpretations; contextualising and providing a clear and easily accessible appraisal of the current simulations for the scientific and applied communities will enhance the scope and application of future research.

2. Free-running soccer-specific exercise protocols

Free-running simulations are intuitively appealing, given their multidirectional nature[28], inclusion of ball skills[24] and higher ecological validity than treadmills.[22] Free-running simulations have also demonstrated an elevated physiological response versus treadmill variants.[29] Numerous participants can simultaneously undertake a free-running simulation, thus, researchers with a time efficient agenda may benefit from the reduced time burden involved with completion. This model also enables players to attain maximum speeds, though players are able to adopt pacing approaches as these simulations are typically externally paced (e.g., running speeds are often guided by audible commands).[30] These simulations tend to closely resemble soccer match dynamics, though incorporating skill tasks within the design may prove complex for technically incapable cohorts, which can jeopardise the physical impetus of the simulation.[10] This type of simulation can also be less desirable in that it appears to be less reproducible compared to treadmill simulations[22] and is unable to mimic the mechanical loading patterns of matches.[18] However, recent investigations directly comparing the kinetics, mechanical and musculotendinous outcomes during over ground and treadmill running, suggest that both are largely comparable.[31] Therefore, it appears that free-running simulations may elicit similar mechanical stressors versus treadmill-based activity whilst overcoming the inherently lower physiological and stress response associated with treadmill running.[18] Table 1 characterises the free-running simulations discussed below.

INSERT TABLE 1

Bishop et al.,[32] were the first research group to document use of a free-running simulation. The total distance covered within university-standard soccer players recruited is uniform with the literature.[2] However, the distances covered at each speed[5, 8, 33] and the frequency of speed changes[5, 34] are not characteristic of professional match-play. The simulation elicited a blood lactate[14] and heart rate[12] response synonymous with match-play, although the intensity was not sufficient to elicit a cortisol response comparable with match data.[35] Thus, although some of the responses are valid, the activity profile does provide an accurate representation of match-play.

The Loughborough Intermittent Shuttle Test (LIST) was later designed and total distance covered is similar to match-play.[1, 2] Part A comprises five 15 min bouts of activity, each interspersed with 3-min passive periods, with the activity based on previous notational data.[6] Part B consists of 20m shuttles performed at running speeds equivalent to 55 and 95% $\dot{V}O_{2max}$ until volitional exhaustion. The LIST is widely used but is characterised by a disproportionate amount of time at high-speed and distances covered at each locomotion category do not resemble match-play. The cardiac demand is significantly lower than actual match-play, possibly due to the recurrent 3-min periods of passive rest.[36] A modified version incorporates additional activities (e.g., zig-zag sprinting)[37], with data suggesting blood lactate concentrations are characteristic of match analyses.[14] The LIST is a linear simulation; however, the original version has been shown to induce greater reductions in hamstring function versus an adapted non-linear version.[38] This could be attributed to the excessive 180 degree turns performed throughout the LIST, with few 180 degree change-of-direction tasks completed during match play.[9] Therefore, validation issues are apparent, with the modified versions better reflective of match-play.

The soccer-specific aerobic field test (SAFT^{90}) is designed to simulate English Championship match-play observations.[28] Closer inspection reveals an overestimation of distances covered per activity bout and almost double the proportion of change-of-direction tasks (n = 1350) versus English Premier League matches.[9] This may artificially inflate the physiological and biomechanical strain, with additional utility movements shown to increase the energy demands versus forward running.[9] The physiological and biomechanical responses to a simulation are usually lower than match-play and, the manipulation in the simulation design could be useful in increasing the response. However, this may largely depend on the research question, and researchers should be conscious of the simulation's validity when incorporating an excessive number of change-of-directions tasks. Thereby, whilst the SAFT[90] may comprise an excessive number of utility movements[9], it may present an appealing option for its reasonable approximation of match-play[28], particularly with research groups that have access to large laboratory spaces or sports halls.

Currell et al.,[39] developed a simulation on an outdoor AstroTurf pitch. The simulation provides an ecologically valid estimate of match-play, based on the utility movements and skill incorporation, as well as the speed changes relative to classic match data.[6] The technical aspects within its design (dribbling, heading and kicking accuracy) are deemed reliable (CV<7.0). However, since the simulation is deemed reliable and valid on a full-length AstroTurf pitch, its use may only be appropriate for those that can access such facilities, especially when considering that pitch surface characteristics can influence running mechanics and post exercise fatigue/recovery responses.[40] The design does not accurately simulate the speed change frequencies ($n = 900$) of contemporary match analyses[9], and there is an absence of physiological and total distance data reported. Therefore, caution must be exercised when interpreting the simulations' validity.

The ball-sport endurance and sprint test (BEAST_{90})[41] is devised based on elite match-play[42-44] but validated using amateur populations. The total distance covered is at the lower end of match data.[41] The BEAST_{90} also incorporates skill actions (shooting tasks) which are not reliable (percentage typical error ≥19.6%), likely due to the skill level of participants. Although simulations typically prescribe individual exercise intensities[24, 28, 45], the BEAST_{90} allows participants to regulate their own running speeds.[41] However, although this might increase ecological validity, the reproducibility may be influenced without appropriate habituation. This simulation is characterised by prolonged periods of stationary activity, and dissimilar moderate-to-high-speed distances versus 90-min soccer matches.[5] An adapted version of the BEAST_{90} with subtle design modifications (omission of skill activity and modifications to the activity) has since improved the reliability, augmenting experimental control (Pearson's correlation coefficient (r) ≥0.65).[46] In sum, the accuracy of the simulation's activity may be questionable[41], but some of the unique features (i.e., the inclusion of self-paced running elements) are advantageous for certain study designs and training applications.

A variation of the LIST, termed the soccer match simulation (SMS), was later designed with the addition of a half-time period and skill actions with both backwards and lateral movemements.[24] The initial validation procedures involved directly comparing the SMS with match-play in the same cohort of players. The SMS has a disproportionate frequency of speed changes (168/90 mins) and prolonged recovery periods that may not capture the highly intermittent demands of match-play.[47] The frequency of on-the-ball activities was originally designed to simulate match data[9], but the numbers identified for the SMS ($n = 93$) are higher than match-play ($n = 59$).[24] Incorporating technical elements within the design adds to the energetic cost versus strictly uni-directional movements[48] and when no ball is present.[49] Notably, using players not adequately skilled and incapable of maintaining ball control may also compromise the exercise intensity.[10] Therefore, researchers choosing a simulation should consider that it is suitable for the ability of the players recruited. The duration of the SMS has been adapted, with the performance and physiological responses deemed moderate-to-strongly reliable (CVs ≤ 8.1%, $r \geq 0.48$) over 120 min.[22] To conclude, the SMS is reliable[22], but the quantity of speed changes are fewer than match-play data[9], thus, the simulation is not entirely valid.

The Copenhagen soccer test (CST)[50] represents distance performed at discrete locomotion categories and the speed profile of a soccer match.[5] The responses to the simulation were compared to player's data in an actual match. This approach is seldom undertaken within the literature, but is recommended for validation.[10, 19] No significant differences are observed between the simulation and a match performed by the same players for heart rate, muscle glycogen and creatine kinase values, suggesting the physiological response to the simulation equated to the competitive match.[50] The design is also complex, and thus, it is recommended that participants are appropriately familiarised with the simulations' procedures to reduce potential learning effects. The simulation also necessitates a vast area, potentially limiting its practical compatibility for researchers with restricted access to a large facility. However, the CST appears to offer a valid method of replicating match-play, given the close physiological approximations and consistency with the activity profile of actual soccer matches.[5]

3. Non-motorised treadmill-based soccer-specific exercise protocols

Laboratory-based simulations offer high experimental control, manipulation and intervention, with non-motorised treadmill (NMT) designs possessing greater ecological validity than motorised treadmill simulations. During NMT simulations, instantaneous accelerations and decelerations are achievable[19], as the athlete consciously decides their speed, consistent with free-running simulations, allowing participants to express maximal running capacity.[51] Yet, it is acknowledged that the NMT belt resistance, may increase the energy cost coinciding with a decrement in maximal sprint speed in comparison with overground running.[52] Another fundamental benefit associated with utilising NMT simulations is that peak sprint speeds can be used to individualise[51] as opposed to setting the running speeds to the work rate of the average player.[53] Athletes with a greater physical capacity can, therefore, attain maximal output, whilst enabling individuals with lower athletic competency to persist within their own capabilities, since real-time measures of power output are displayed.[54] However, players with increased maximal sprint speed and a lower aerobic capacity, may demonstrate exacerbated fatigue responses within the latter stages of the simulation. In comparison, players with a higher $\dot{V}O_{2\max}$ and less reliant on maximal sprint speed, could have a diminished fatigue response at the same period of play, potentially not displaying a player's true maximal capacity within the simulation. The evolutions in the NMT models, such as the curved design, promotes a natural running gait facilitating a longer stride length and swing phase, typically observed during over ground running.[55] It is key, however, that prudence is applied to coordinating the various speeds for each locomotion category (walk, jog, run etc.)[19] to correct for the high degree of propulsion required to overcome the inertia of the treadmill belt resistance.[56] Some of the fundamental limitations that apply to NMT simulations are that utility movements (sideways and backwards activity) and skill performance cannot be modelled, as well as pacing strategies are not entirely precluded.[26] Table 2 provides specific NMT simulation details.

INSERT TABLE 2

The first NMT simulation was developed by Drust et al.,[57] using time-motion analysis literature from international players.[58] The distances are similar to match-play[59]; however, the simulation has fewer locomotion changes (*n*=198) versus match data.[9] A modified version has been developed[60, 61], replacing the frequency of stationary and walking periods with time spent at higher speeds, and incorporating a higher quantity of speed changes. The adjustments to the newer model may more closely represent match scenarios, yet the proportion of time in each speed category remains less than notational data.[8, 33] Therefore, although the simulation is a close representation of match data ~20 years prior[58], researchers intending to use the simulation are advised to reconsider the quantity of speed changes to accurately conform with contemporary match running performance.[62]

Thatcher and Batterham[53] developed a NMT simulation with the total distance[5], heart rate[12] and blood lactate[14] responses similar to English Premier League match evaluations in the study. The activity patterns of simulations are generally aggregated amongst all outfield positional roles[63], but for discernible evaluations, the authors displayed external load profiles for each playing position.[53] It may, however, be refuted that the differing cohorts used for development and subsequent validation, likely limit the confidence with which the simulation can be regarded an accurate resemblance of match-play. The number of speed changes (10—20-s) equates to 450—540 changes in activity; fewer than described throughout an entire match.[9] Therefore, the current simulation provides a controlled exercise stimulus that can be used as a reference point for position-specific external load metrics[53], though may not be accurate for simulating current match data.[62]

The soccer-specific intermittent-exercise test (SSIET) is designed to simulate the demands of one-half of English Premier and Championship league matches.[59] The locomotion categories are based on a previous simulation[20], which used match profiles to obtain speed distributions.[58] Sprint distances (*n* = 551 m) are homogenous with the upper-limit of match analyses.[2, 5] Both mean heart rate (173—176 bpm^{-1}) and blood lactate data (6.57—7.24 mmol·l^{-1}) elicited by the SSIET are consistent with match-play values (165—175 bpm^{-1}[12], 2—10 mmol·l^{-1}).[14] However, it could be argued that blood lactate data is not sufficient to validate the simulation, given the values elicited are highly dependent upon the effort level and speed profile instantly before sampling.[50] The performance responses demonstrate high test-retest reliability (CVs = 2.5—7.9%) and the SSIET elicits an analogous physiological profile with matches.[12, 14] However, the SSIETs activity profile may not be a valid representation of match-play, given the specific speeds assigned to each category are based on a simulation using outdated match data for an individual position.[20]

The intermittent soccer performance test (iSPT)[51] was later developed and is an accurate interpretation of previous match-play data for duration and speed change frequency.[9] The test re-test reliability of the performance and physiological responses to the iSPT yielded good agreement (CV ≤4.6%, intraclass correlation coefficient [ICC] ≥0.80). The simulation also proposed a novel element which comprised a 'variable run', designed to tailor individual speed thresholds to delimit high-speed exercise above the second ventilatory threshold.[51] Overall and self-paced high-speed running assessed via the variable run and sprint distance covered demonstrated fatigue responses during both the second half and final periods (75—90 min) of iSPT, in parity with match-play. The blood lactate concentrations evoked during the simulation are close to reported match samples[14] whilst heart rate values fall marginally below professional soccer match-play data.[12] The University-level players may not be representative of the population against which the simulation is based, although, participants with a $\dot{V}O_{2max}$ $\geq$55mL.kg^{-1}.min^{-1} are recruited, similar with professional soccer.[64] To summarise, the iSPT is an accurate representation of match-play and thus, is recommended for use within the confines of its limitations..

4. Motorised treadmill-based soccer-specific exercise protocols

Motorised treadmill simulations are arguably the least ecologically valid, though offer the ultimate in experimental control. Motorised treadmill simulations facilitate the implementation of fixed periods of activity, omitting subconscious pacing elements and attaining close replication of the speed profile to elicit a biomechanical fatigue response comparable to match-play.[65] Considering distances and speeds are standardised (both across time periods and between participants), gives researcher assurance that within-exercise changes observed in a given measure are likely due to fatigue, rather than pacing or player motivation.[66] It must also be considered that treadmills are essential for certain types of research, for example studies involving climate chambers[51] or when a controlled model is required. Thought must also be applied to employing a pseudorandom activity simulation to ensure players are unable to predict upcoming speed changes, thus, imitating the stochastic distribution of match-play.[16] As the speed of the motorised treadmill belt remains constant until actively changed, safety precautions with the harness are required. This could impede natural running mechanics[67], coupled with fatigue-induced compensatory adjustments in gait, possibly increasing soft-tissue injury-risk.[66] However, motorised treadmill simulations are also generally less effective for eliciting valid physiological data (as evidenced by small changes in biochemical milieu)[65], sprinting speeds are not always reached and the treadmill itself can be expensive versus the cost-effectiveness of field-based simulations. All motorised-treadmill-based simulations included in this section are characterised in Table 3.

INSERT TABLE 3

To the authors knowledge, Abt et al.,[68] were the first group to document the development of a treadmill-based simulation. The total distance covered during the simulation is comparable with match-play[5], and the physiological response (heart rate[12] and blood lactate[14]) is consistent with match analyses. However, the validity of the simulation is questionable, as there exists a low frequency of changes in locomotion versus match-play data.[34] The authors proposed a solution to simulate outdoor running mechanics, which involved manipulating a feature of the treadmill design to incorporate changes in both treadmill speed and gradient. Previous research demonstrates that applying a treadmill gradient of 1% elicits an energy cost equal to outdoor running at lower speeds, whilst a 2% inclination better reflects high-speed activity (18 km·h^{-1}).[69] However, it is unclear whether such alterations to the treadmill gradient influences running mechanics. Considering that the simulation lasts for 61 min (29-min shorter than a soccer match), though reaches match distances, the distance at each movement category is likely excessive, and as such, there are evidently validity issues.

Drust et al.,[70] developed a simulation that was synonymous with the proportion of time spent in each locomotion activity during match observations published in 1976.[6] The protocol is 45 min in duration, thus, representing one-half of a match, with players covering an excessive total distance (10 km in 45 min). The oxygen demand of the simulation (68% $\dot{V}O_{2max}$) closely compares to the oxygen cost of competing in competitive matches (70% $\dot{V}O_{2max}$).[7] When averaged across the simulation, heart rate data are 168 ± 10 bpm^{-1}, which are within the limits of previous match values.[12] However, whether the physiological response can be used to validate the use of the simulation is somewhat limited. Especially considering the duration of each discrete block of activity is much greater than contemporary professional soccer matches[5], thus, likely not reflective of the intermittent nature of match-play.[9] To summarise, the simulation is based on dated soccer match analyses[6] and overestimates the distances covered during professional soccer matches.[5]

A simulation was developed[71] to simulate the duration of each discrete bout of activity as prescribed by notational analysis data[72], and accurately reflects the frequency of speed change reported in contemporary matches.[5, 34] This is evident from the salivary markers of cortisol taken during the simulation (~14.5—17.5 nmol·l^{-1}), which demonstrates an endocrine stress response similar to a soccer match.[35] Backwards running is unable to be safely incorporated on a treadmill, thus, additional low-speed running is performed during the simulation to accommodate the absence of backward activity.[35] However, given that the physiological response is considerably lower than that observed during match-play,[7, 15, 42, 73, 74] the current simulation is not an accurate representation of the physiological strain of an actual game.[15, 73, 74]

The most contemporary motorised treadmill-based simulation was developed by Page et al.,[18]. The distances covered are concomitant with those reported during match observations[5, 8] and the biomechanical demands (accelerometry-derived metric PlayerLoad™) appear largely similar to data collected from English championship match-play.[75] Varying degrees of gradient are applied to the simulation to account for the absence of air resistance associated with indoor running[69], with the quantity of speed changes (n=1386) analogous with match-play.[9] The simulation's running patterns are 'clustered' to mimic contemporary match structures[76], potentially explaining the finding that blood lactate values (3.2 ± 2.1 mmol·l^{-1}) are near the lower limit of within-match data.[14] The simulation has since demonstrated moderate-to-very-strong reliability for biomechanical and physiological variables (CV ≤10%, r = 0.33–0.99).[66] Therefore, this simulation offers a reliable method and is arguably the most valid design when compared to the other motorised treadmill variants reviewed in this section. However, the lower physiological cost needs to be considered and potentially could be elevated by inducing additional cognitive load, or via slight modifications to the design.

5. Practical applications and future research directions

The simulations reviewed throughout are entirely distinct and must be considered within the operational context of their use. Table 4 provides guidance by which decision-making processes can be better directed towards improving the application of future soccer-specific research. It is proposed that researchers and practitioners refer to this guide when selecting a suitable simulation design concerning the research objective or application in the practical setting.

INSERT TABLE 4

Considered from a fatigue-management perspective, free-running simulations may be used for highly specific 'top-up' conditioning work for partial-match players (substitutes/those being replaced)[77, 78] as opposed to general fitness sessions. Using simulations might offer new avenues for training with reference to late-stage return-to-play rehabilitation and provide a progressive mechanical strain that closely duplicates an actual match.[65] Initially, treadmill-based variants may be suitable to preclude change-of-direction elements associated with non-contact loading-related knee injuries.[79] Progressive loading may then be facilitated by the execution of strenuous utility movements and soccer-specific tasks associated with free-running simulations.[22] Performing free-running simulations on natural turf appears appropriate for early rehabilitation to prevent exacerbating residual hamstring fatigue associated with artificial surfaces[40], potentially increasing injury-risk. Practitioners examining the physical capacity of players, instead of replicating match demands, are advised to use the YYIR level 1[80] or level 2 test.[81] Research groups must also be cognisant that assessments merely designed to measure technical components (Loughborough Soccer Passing and Shooting Tests[82]) cannot be used as appropriate surrogates for match-play. Indeed, testing fitness and technical components can provide coaches with objective feedback, including an indication of distinctive strengths and deficiencies.[83] However, given the acquisition of game skills and the increased energy expenditure of exercising with the ball[49], free-running simulations integrating skill components are likely beneficial for preparation for competition and maintaining technical training stimuli.

A major limitation of current simulations, as a general observation, is that they fail to simulate the spontaneity of matches (e.g., reacting to opposition manoeuvres), with movements able to be anticipated by players, thus, not reflecting the sporadic and random nature of match-play.[16] Innovative researchers could design simulations that imitate the authentic aspects of soccer by replicating a competitive environment (i.e., crowd, score, opponent etc), that is currently absent within laboratory- or field-based simulations. This may provide an environment that simulates the psychological pressures experienced within competitive soccer, and thus, enable mental fatigue assessments with greater ecological validity.[84] Virtual reality systems are being developed to enhance the transfer of simulations to real word environments.[85] Such systems may be used in conjunction with treadmill-based soccer-specific simulations to challenge perceptual-cognitive processes (e.g., decision-making) for research and training purposes.

The majority of simulations are validated based on outdated matches (mid-1970s until early-2000s), with the demands of match-play fast evolving.[47, 62] Therefore, it is key that novel simulations are developed at the same rate to capture and simulate the constantly changing demands. There are simulations available to simulate the additional 30-min demands of extra-time for both free-running[22] and motorised treadmills.[66] Furthermore, marked physiological[86] and physical fitness differences between sexes exist.[87] However, to date, the bespoke validation of simulations in female soccer players is outstanding, and as such, limits their applicability for this population. The same applies to goalkeepers, with a paucity of research validating simulations to the unique demands of this specialised position.[88] Despite the feasible challenges involved with recruiting specific cohorts and investigating distinctive aspects of the game, this absence should be addressed moving forward.

The discrete simulations discussed above are difficult to compare given the wide variety of study designs, conditions (dietary restrictions, temperature etc.), monitoring devices, reported outcomes and populations (elite, sub-elite or amateur) recruited within the literature. However, future research should consider participant recruitment strategies, since the playing level of participants likely influence the overall simulation characteristics. This is particularly important given high-speed running performance is greater in elite players[5], perhaps leading to misinterpretations of a simulations' validity. It appears that soccer science research is replete with underpowered studies, which is likely a function of the logistical burden of recruiting specialised populations and the large time and effort commitment of exercise testing. This is also apparent in the included simulation studies with samples sizes ranging from 7 to 18 participants. Insufficient sample sizes can increase the probability of type 2 errors and reduce the likelihood of detecting small-moderate differences.[19] Therefore, for the mutual benefit of researchers and practitioners, future work should tackle this matter through carefully periodising testing schedules at appropriate times of the playing season. Match running profiles also differ between playing positions[47], potentially impacting the physiological response to the simulation. Thus, to ascertain a clearer picture of the simulations demands, a range of positional roles should be incorporated within the initial validation stages.

This article provides a detailed analysis of the individual simulations present within the literature. It is recommended that researchers consider the critical reflections within the current article and use these as a guide to inform their choice of simulation. For specific considerations of each simulation, readers are advised to refer to the above sections. However, as general guidance, free-running simulations have ecologically valid characteristics and should be utilised for studies that are focused on playing surfaces[40], technical actions[24] and change-of-direction tasks.[28] Motorised and NMT laboratory-based simulations possess high experimental control and are efficacious for assessing the influence of the temperature and altitude on physical performance.[25] These designs also provide a progressive 'real' match dynamic to facilitate return-to-play, as they do not contain multidirectional movements (e.g., twisting and turning).[65] The NMT may be preferred to individualise speed thresholds[51], whilst the fixed bouts associated with motorised treadmills eliminates pacing[65] and elicits reliable data.[18] It is advised that future work validating simulations are designed to imitate the evolving and irregular demands of match-play. Novel simulations should be geared towards the development of original ideas that simulate authentic competitive conditions.

Declaration of interest

The authors declare no competing interests

Funding

The authors report that there is no funding associated with the production of this article

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Table 1. A summary of the demands of novel free-running soccer-specific exercise protocols

Reference	Protocol	Notational data	Participants	Duration	Distance	Activity profile	Locomotion changes	Change of direction tasks	Technical actions and utility movements
Bishop et al.,[13]	—	Bangsbo[44]	8 university-standard soccer players	2 x 45 min halves with 15 min passive half-time period	9.7 km	6 x14 min bouts of 7 x 2 min circuits which comprised 50 m walk, 50 m backwards run, 25 m cruise run, 25 m sprint and 50 m dribbles	*n* = 168	*n* = 336	Ball dribbling and backwards running
Nicholas et al.,[47]	Loughborough intermittent shuttle test (LIST)	Reilly[8] Withers[46]	7 trained soccer and rugby players	Part A: 5 x 15 min bouts with 3 min rest Part B: A run (~10 min) to volitional exhaustion	12.4 km	Part A: Repeated 3 x 20 m walks, 1 x 20 m sprint, 4s rest, 3 x 20 m at 55% $\dot{V}O2_{max}$, and 3 x 20 m at 95% $\dot{V}O2_{max}$ Part B: Alternate 20m shuttles at 55 and 95% $\dot{V}O2max$ until volitional exhaustion	Unable to be ascertained	Unable to be ascertained	15 m sprint tests
Small et al.,[28]	Soccer-specific aerobic field test (SAFT[90])	2007 English Championship Level match data	9 semi-professional soccer players	2 x 45 min halves with 15 min passive half-time period	10.8 km	Repeated 15 min bouts of 20 m shuttle activity with speeds and activity directed by audio cues. Navigate the initial pole (2 m from start) with either backwards or lateral movement, run forwards through the course whilst side stepping the 3 middle poles	*n* = 1269	*n* = 1350	10 m sprint tests

Currell et al.,[41]	—	Reilly[8]	11 university-standard soccer players	2 x 45 min halves with 15 min passive half-time period	Total distance undisclosed	10 x 6 min with 4 x repeated 90 s blocks which comprised walking (10 s), jogging (10 s; 50% PSS), cruising (10 s; 95% PSS), jogging (10 s), cruising (10 s), walking (15 s), sprinting (5 s), jogging (15 s), and sprinting (5 s)	*n* = 192	Unable to be ascertained	Agility, kicking, dribbling and heading accuracy tests Backwards, sideways and jumping movements
Williams et al.,[43]	Ball-sport endurance and sprint test (BEAST$_{90}$)	Withers[46] Mayhew and Wenger[45] Bangsbo[44]	15 healthy amateur soccer players	2 x 45 min halves with 15 min passive half-time period	8.1 km	Repeated completion of 2 x laps of a 380 m circuit comprising sprints (8.4%), backward jog (8.4%), walk (9.7%), jog/decelerations (24.5%), run at ~75% of maximum effort (39%), jumping and shooting tasks	*n* = 903	Unable to be ascertained	Vertical jumps and shooting tasks
Russell et al.,[25]	Soccer match simulation (SMS)	Bloomfield et al.,[11]	15 academy soccer players	2 x 45 min halves with 15 min passive half-time period	10.1 km	7 x 4.5 min periods of activity with 3 x repeated cycles of 3 x 20 m walking, alternate 20 m dribbling test or 15 m sprinting, a 4s rest, 5 x 20 m jogs at 40% $\dot{V}$O2max, 1 x 20 m backwards jog at 40% $\dot{V}$O2max, and 2 x high-speed runs completed at 85% of predicted $\dot{V}O2_{max}$. Following each bout, a 1 min passing test and 1 min passive rest was completed	*n* = 126	Unable to be ascertained	Dribbling, passing and shooting tasks Backwards jogging

Bendiksen et al.,[49]	Copenhagen soccer performance test (CST)	Bangsbo[44] Mohr et al.,[2]	12 Danish 2nd and 3rd Division soccer players	2 x 45 min halves with 15 min passive half-time period	11.2 km	18 x 5 min periods of activity comprised of walking (152 m; ~6 km·h^{-1}), jogging (171 m; ~8 km·h^{-1}), low (69 m; ~12 km·h^{-1}), moderate (41m; ~15 km·h^{-1}), high-speed running (55m; ~18 km·h^{-1}); sprinting (2 x 20m; ~6 km·h^{-1}), backwards running (30 m; ~8 km·h^{-1}), and backwards or sideways running (20 m; ~8 km·h^{-1}).	Unable to be ascertained	Unable to be ascertained	Dribbling, passing, shooting and heading tasks Backwards and sideways running

Note. $\dot{V}O2_{max}$ = Maximal oxygen consumption, PSS = Peak sprint speed

Table 2. A summary of the demands of novel non-motorised soccer-specific simulations

Reference	Protocol	Notational data	Participants	Duration	Distance	Activity profile	Locomotion changes	Work-to-rest ratios	Pacing
Drust et al.,[57]	—	Drust et al.,[57]	17 professional soccer players	2 x 45 min halves with 15 min passive half-time period	9.5 km	3 x 5 min cycles with 11 repeated activities which comprised 3 x standing (0 km·h^{-1}), 3 x walking (4 km·h^{-1}), 3 x jogging (8 km·h^{-1}), 1 x cruising (12 km·h^{-1}) and 1 x sprinting (maximal).	$n = 198$	Unable to be ascertained	No specific description of pacing was present
Thatcher and Batterham[53]	—	1998—99 English Premier League first team and academy match data	12 professional and 12 youth professional academy players	2 x 45 min halves with 15 min passive half-time period	9.7—10.3 km	9 x 5 min repeated cycles which comprised 3 x standing (3.64s x 4; 0 km·h^{-1}), 8 x walking (4.3 s x 4; 5 km·h^{-1}), 7 x jogging (3.58 s x 4; 10 km·h^{-1}), 2 x running (3.82 s x 3; 17 km·h^{-1}) and 1 x sprinting (2.8s; 23 km·h^{-1})	$n = 378$	8:1	Participants were given a visual cue that displayed the treadmill and target speed, with a 3-second countdown to inform of the approaching speed change
Oliver et al.,[59]	Soccer-specific intermittent-exercise test (SSIET)	Drust et al.,[57]	12 youth soccer players	3 x 14 min bouts of exercise with 3 min passive rest	4.8 km	7 x 2 min periods which comprised 45 s walking (4 km·h^{-1}), 15 s cruising (12 km·h^{-1}), 15 s stationary, 40 s jogging (8 km·h^{-1}) and a 5 s maximal sprint	$n = 105$	3:1	Participants were verbally instructed at the point whereby a speed change was required, and a visual display monitor was used to control speed
Aldous et al.,[51]	The intermittent soccer performance test (iSPT)	Bangsbo[44] Withers[46]	12 university-standard soccer players	2 x 45 min halves with 15 min passive half-time period	8.9 km	3 x 15 min comprised of standing (0% PSS), walking (20% PSS), jogging (35% PSS), running (50% PSS), fast running (60% PSS), variable run (unset), sprinting (100% PSS)	$n = 690$	5:3	The target running speed was attained by following a red line on the screen and audible tones were played to inform of the upcoming speed change

Table 3. A summary of the demands of novel motorised soccer-specific exercise protocols

Reference	Notational data	Participants	Duration	Distance	Activity profile	Locomotion changes	Work-to-rest ratios	Gradient
Abt et al.,[66]	Undisclosed	6 midfield trained recreational soccer players	60 min	11.2 km	9 x cycles which comprised 5 min medium-speed running (individualised), 30 s high-speed running (individualised) and 75 s low-speed (4 km·h^{-1}). High and medium speeds corresponded to 100 and 75 % of an individual's $\dot{V}O2_{max}$	*n* = 27	13:1	A range of gradients (0—7 %) were applied to the activity profile
Drust et al.,[68]	Reilly[8]	7 university soccer players	45 min	10 km	2 x 22.5-min cycles which comprised 6 x walking (35.3 s; 6 km·h^{-1}), 6 x jogging (50.3 s; 12 km·h^{-1}), 3 x cruising (51.4 s; 15 km·h^{-1}) and 8 x sprinting (10.5 s; 21 km·h^{-1})	*n* = 92	Unable to be ascertained	Gradient undisclosed
Greig et al.,[69]	Bangsbo[70]	10 semi-professional soccer players	2 x 45 min halves with 15 min passive half-time period	9.7 km	6 x 15 min which comprised 20 x standing (7.8 s; 0 km·h^{-1}), 55 x walking (6.7 s; 4 km·h^{-1}), 42 x jogging (3.5 s; 8 km·h^{-1}), 46 x low-speed running (3.5 s; 12 km·h^{-1}), 20 x moderate-speed running (2.5 s; 16 km·h^{-1}), 9 x high-speed running (2.1 s; 21 km·h^{-1}) and 3 x sprinting (2.0 s; 25 km·h^{-1})	*n* = 894	5:1	A gradient of 2% was applied to the activity profile throughout
Page et al.,[16]	Mohr et al.,[2]	18 semi-professional soccer players	2 x 45 min halves with 15 min passive half-time period	12.2 km	6 x 15 min which comprised 29 x standing (7.0 s; 0 km·h^{-1}), 65 x walking (6.4 s; 4 km·h^{-1}), 53 x jogging (3.0 s; 8 km·h^{-1}), 48 x low-speed running (2.6 s; 11.6 km·h^{-1}), 17 x moderate-speed running (2.2 s; 15 km·h^{-1}), 12 x high-speed running (2.1 s; 18 km·h^{-1}) and 7 x sprinting (2.5 s; 25 km·h^{-1})	*n* = 1386	3:1	A range of gradients (1—2.5%) were applied to the activity profile

Note. PSS = Peak sprint speed

Table 4. General considerations for the different soccer-specific exercise protocol designs and the research and practical applications of each design

Consideration	Free running	Non-motorised treadmill	Motorised treadmill
Is the design ecologically valid?	✓✓	✓	X
Does the design elicit experimental control?	X	✓	✓✓
Are the responses to the design reproducible?	✓	✓	✓✓
Are self-pacing approaches precluded?	X	✓	✓✓
Does the design enable players to reach their peak sprint speeds?	✓✓	✓	XX
Does the design enable players to reach their maximal aerobic capacity?	✓	✓	XX
Can the design be individualised to a specific players' aerobic capacity/peak sprint speed?	✓	✓✓	XX
Can technical actions be implemented within the design?	✓✓	XX	XX
Does the design require access to large spaces?	XX	✓✓	✓✓
Is the design time efficient (i.e., multiple participants can be tested)?	✓✓	XX	XX
Is the design complex?	X	✓	✓✓
Is the design cost effective?	✓✓	XX	X
Research and Practical Application			
Assessing the impact of environmental stress on performance	X	✓✓	✓✓
Investigating the efficacy of nutritional/non-nutritional interventions	✓✓	✓✓	✓✓
Evaluating change of direction tasks	✓✓	XX	XX
Assessing the influence of playing surfaces on performance	✓✓	XX	XX
Substitution conditioning	✓✓	✓	✓
Early stages of rehabilitation following injury	X	✓	✓✓
Late stage return-to-play following injury	✓✓	✓	X
Total	**24**	**18**	**18**

Note. ✓ denotes positive, ✓✓ denotes very positive, **X** denotes negative, **XX** denotes very negative.

For total scores: ✓✓ = 2, ✓ = 1, **X** = 0.5, **XX** = 0.