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9 **Authors:** Adam C. Field<sup>1, 2\*</sup>, Liam D. Harper<sup>1</sup>, Jeffrey W. F. Aldous<sup>3</sup>, Richard M. Page<sup>4</sup>

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11 <sup>1</sup>University of Huddersfield, School of Human and Health Sciences, Huddersfield, HD1 3DH, United  
12 Kingdom.

13 <sup>2</sup>Nuffield Health, The Manchester Institute of Health and Performance, Alan Turing Way, Openshaw,  
14 Manchester M11 3BS

15 <sup>3</sup>University of Bedfordshire, Department of Sport Science and Physical Activity, Institute of Sport and  
16 Physical Activity Research, Bedford, United Kingdom.

17 <sup>4</sup>Edge Hill University Department of Sport & Physical Activity, St. Helens Road, Ormskirk, Lancashire,  
18 L39 4QP, United Kingdom.

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20 **\*Author responsible for correspondence:**

21 Adam Field, [Adam.field@nuffieldhealth.com](mailto:Adam.field@nuffieldhealth.com).

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

58  
59 **Keywords:** Football · field-based · free-running · treadmill · protocol

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## 77 1. Introduction

78 During 90 min competitive soccer matches, professional male players cover 8.9—11.8 km total  
79 distance<sup>1, 2</sup>, 0.7—3.9 km high-speed distance<sup>3, 4</sup>, 0.2—0.6 km sprint distance<sup>2, 5</sup>, and perform  
80 1000—1500 locomotion changes<sup>5-8</sup>, ~726 change-of-direction movements<sup>9</sup> and 50—110 technical  
81 actions.<sup>9-11</sup> Match-play also elicits a heart rate response of 159—175 bpm<sup>-1</sup><sup>12, 13</sup>, blood lactate values of  
82 2.4—10 mmol·l<sup>-1</sup><sup>13, 14</sup> and a mean of 70% maximal oxygen uptake ( $\dot{V}O_{2max}$ ).<sup>14, 15</sup> However, soccer  
83 matches are susceptible to external factors<sup>16, 17</sup> and the match-to-match variability in some of these  
84 metrics is high (e.g., high-speed running).<sup>18</sup> Given these features, researchers face a challenging trade-  
85 off between higher external and internal validity.<sup>15, 17</sup> A minimum sample size of 80 (using a coefficient  
86 of variation [CV] of 20%) would be required to determine a meaningful impact of an intervention on  
87 within-match performance metrics.<sup>16</sup> However, recruiting such large samples of elite players for  
88 research is challenging.<sup>19</sup> Therefore, soccer simulation protocols have been developed to reduce the  
89 limitations outlined above when using real match-play for research. Although simulations are less  
90 ecologically valid versus a competitive soccer match, such exercise models control the movement  
91 demands and elicit repeatable physiological responses whilst attempting to simulate match-play for both  
92 research and training.<sup>10</sup>

93  
94 Early developments in soccer simulations during the late 1990s were derived from manually computing  
95 the proportion of time spent in each movement category using video match footage of an individual  
96 player.<sup>20</sup> Using such methodologies to design a model that accurately simulates the demands of match-  
97 play is likely limited due to the potential inaccuracies associated with data processing and the skewed  
98 values involved with basing the simulation on an individual players' activity profile. Critical debate has  
99 occurred within the literature concerning the validation requirements of soccer simulations.<sup>10, 19</sup> For  
100 validation, researchers have reported the importance of a single population of players completing both  
101 the simulation and match-play with statistical comparisons being made between both exercise modes.<sup>10,</sup>  
102 <sup>19</sup> The activity profile is typically validated against notational analyses of match-play, however,  
103 simulations must also be validated based on both input (distance, duration, and activity profile)<sup>18</sup> and  
104 output (energy requirements, heart rate, blood lactate,  $\dot{V}O_2$  profiles and mechanical demands).<sup>19</sup> This  
105 becomes difficult considering that soccer is characterised by an intermittent and irregular activity  
106 profile, thus, increasing the complexity of both the biomechanical loading patterns and physiological  
107 response. Simulations also provide a safe and reproducible exercise stimulus that guards against  
108 physical contact, which is responsible for >70% of injuries during match-play.<sup>21</sup> As such, simulations  
109 are developed to safely simulate the activity profile associated with match-play for training purposes,  
110 but each designed with a specific application in mind.

111  
112 Soccer simulation variants can be broadly categorised as either, free-running (also known as over  
113 ground or field-based) or treadmill-based (motorised or non-motorised). Free-running simulations  
114 closely reflect the physiological profile of match-play and possess higher ecological validity than  
115 treadmills.<sup>22</sup> Conversely, treadmill-based simulations elicit an analogous biomechanical fatigue  
116 response with match-play and offer increased experimental control.<sup>18</sup> The researcher must decide which  
117 type of simulation is most suitable for use relative to the research question posed. A study investigating  
118 change-of-direction<sup>23</sup> or technical aspects (e.g., dribbling skills)<sup>24</sup> may necessitate a free-running  
119 simulation. Whereas, a study investigating the effect of environmental stressors on physical  
120 performance and physiological responses within an environmental chamber<sup>25, 26</sup>, should utilise a  
121 laboratory-based treadmill simulation. Primarily, the type of simulation must be considered on a  
122 continuous scale with match-play (higher ecological validity) and treadmill-based simulations (higher  
123 experimental control) at opposing ends akin to the basic-applied research continuum.<sup>19, 27</sup> To many  
124 researchers, simulating the demands of soccer is widely considered a reproducible alternative to match-  
125 play, although there is a lack of consensus for selecting the appropriate design in relation to the research  
126 outcomes. Therefore, given the importance of simulations and the difficulties that currently exist for  
127 researcher interpretation of the varying exercise modes for simulating match demands, summarising the  
128 key information appears warranted to improve the application of future research.

129  
130 To date, two review articles exist that provide an evaluation of published research involving  
131 simulations.<sup>10, 19</sup> While such reviews have merit, both were published >10 years prior and there has

132 since been a marked increase in the number of simulations developed. Accordingly, the current article  
133 provides a commentary of the simulations with a view to guiding researchers and practitioners in  
134 making informed decisions on simulation selection. Such an appraisal appears warranted to facilitate  
135 the adoption of the most suitable study designs and to highlight the varying applications of each of the  
136 simulation types within the applied setting. Considering the influx of contrasting interpretations;  
137 contextualising and providing a clear and easily accessible appraisal of the current simulations for the  
138 scientific and applied communities will enhance the scope and application of future research.  
139

## 140 **2. Free-running soccer-specific exercise protocols**

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

158 \*\*\*INSERT TABLE 1\*\*\*

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

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

179 The soccer-specific aerobic field test (SAFT<sup>90</sup>) is designed to simulate English Championship match-  
180 play observations.<sup>28</sup> Closer inspection reveals an overestimation of distances covered per activity bout  
181 and almost double the proportion of change-of-direction tasks ( $n = 1350$ ) versus English Premier  
182 League matches.<sup>9</sup> This may artificially inflate the physiological and biomechanical strain, with

183 additional utility movements shown to increase the energy demands versus forward running.<sup>9</sup> The  
184 physiological and biomechanical responses to a simulation are usually lower than match-play and, the  
185 manipulation in the simulation design could be useful in increasing the response. However, this may  
186 largely depend on the research question, and researchers should be conscious of the simulation's  
187 validity when incorporating an excessive number of change-of-directions tasks. Thereby, whilst the  
188 SAFT<sup>90</sup> may comprise an excessive number of utility movements<sup>9</sup>, it may present an appealing option  
189 for its reasonable approximation of match-play<sup>28</sup>, particularly with research groups that have access to  
190 large laboratory spaces or sports halls.

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

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

214 A variation of the LIST, termed the soccer match simulation (SMS), was later designed with the addition  
215 of a half-time period and skill actions with both backwards and lateral movements.<sup>24</sup> The initial  
216 validation procedures involved directly comparing the SMS with match-play in the same cohort of  
217 players. The SMS has a disproportionate frequency of speed changes (168/90 mins) and prolonged  
218 recovery periods that may not capture the highly intermittent demands of match-play.<sup>47</sup> The frequency  
219 of on-the-ball activities was originally designed to simulate match data<sup>9</sup>, but the numbers identified for  
220 the SMS ( $n = 93$ ) are higher than match-play ( $n = 59$ ).<sup>24</sup> Incorporating technical elements within the  
221 design adds to the energetic cost versus strictly uni-directional movements<sup>48</sup> and when no ball is  
222 present.<sup>49</sup> Notably, using players not adequately skilled and incapable of maintaining ball control may  
223 also compromise the exercise intensity.<sup>10</sup> Therefore, researchers choosing a simulation should consider  
224 that it is suitable for the ability of the players recruited. The duration of the SMS has been adapted, with  
225 the performance and physiological responses deemed moderate-to-strongly reliable ( $CVs \leq 8.1\%$ ,  $r \geq$   
226  $0.48$ ) over 120 min.<sup>22</sup> To conclude, the SMS is reliable<sup>22</sup>, but the quantity of speed changes are fewer  
227 than match-play data<sup>9</sup>, thus, the simulation is not entirely valid.

228 The Copenhagen soccer test (CST)<sup>50</sup> represents distance performed at discrete locomotion categories  
229 and the speed profile of a soccer match.<sup>5</sup> The responses to the simulation were compared to player's  
230 data in an actual match. This approach is seldom undertaken within the literature, but is recommended  
231 for validation.<sup>10, 19</sup> No significant differences are observed between the simulation and a match  
232 performed by the same players for heart rate, muscle glycogen and creatine kinase values, suggesting  
233 the physiological response to the simulation equated to the competitive match.<sup>50</sup> The design is also

234 complex, and thus, it is recommended that participants are appropriately familiarised with the  
235 simulations' procedures to reduce potential learning effects. The simulation also necessitates a vast  
236 area, potentially limiting its practical compatibility for researchers with restricted access to a large  
237 facility. However, the CST appears to offer a valid method of replicating match-play, given the close  
238 physiological approximations and consistency with the activity profile of actual soccer matches.<sup>5</sup>

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

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

262  
263 \*\*\*INSERT TABLE 2\*\*\*

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

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

283 The soccer-specific intermittent-exercise test (SSIET) is designed to simulate the demands of one-half  
284 of English Premier and Championship league matches.<sup>59</sup> The locomotion categories are based on a

285 previous simulation<sup>20</sup>, which used match profiles to obtain speed distributions.<sup>58</sup> Sprint distances ( $n =$   
286 551 m) are homogenous with the upper-limit of match analyses.<sup>2, 5</sup> Both mean heart rate (173—176  
287 bpm<sup>-1</sup>) and blood lactate data (6.57—7.24 mmol·l<sup>-1</sup>) elicited by the SSIET are consistent with match-  
288 play values (165—175 bpm<sup>-12</sup>, 2—10 mmol·l<sup>-1</sup>).<sup>14</sup> However, it could be argued that blood lactate data  
289 is not sufficient to validate the simulation, given the values elicited are highly dependent upon the effort  
290 level and speed profile instantly before sampling.<sup>50</sup> The performance responses demonstrate high test-  
291 retest reliability (CVs = 2.5—7.9%) and the SSIET elicits an analogous physiological profile with  
292 matches.<sup>12, 14</sup> However, the SSIETs activity profile may not be a valid representation of match-play,  
293 given the specific speeds assigned to each category are based on a simulation using outdated match data  
294 for an individual position.<sup>20</sup>

295 The intermittent soccer performance test (iSPT)<sup>51</sup> was later developed and is an accurate interpretation  
296 of previous match-play data for duration and speed change frequency.<sup>9</sup> The test re-test reliability of the  
297 performance and physiological responses to the iSPT yielded good agreement (CV ≤4.6%, intraclass  
298 correlation coefficient [ICC] ≥0.80). The simulation also proposed a novel element which comprised a  
299 ‘variable run’, designed to tailor individual speed thresholds to delimit high-speed exercise above the  
300 second ventilatory threshold.<sup>51</sup> Overall and self-paced high-speed running assessed via the variable run  
301 and sprint distance covered demonstrated fatigue responses during both the second half and final periods  
302 (75—90 min) of iSPT, in parity with match-play. The blood lactate concentrations evoked during the  
303 simulation are close to reported match samples<sup>14</sup> whilst heart rate values fall marginally below  
304 professional soccer match-play data.<sup>12</sup> The University-level players may not be representative of the  
305 population against which the simulation is based, although, participants with a  $\dot{V}O_{2max}$   
306 ≥55mL.kg<sup>-1</sup>.min<sup>-1</sup> are recruited, similar with professional soccer.<sup>64</sup> To summarise, the iSPT is an  
307 accurate representation of match-play and thus, is recommended for use within the confines of its  
308 limitations..

309

#### 310 **4. Motorised treadmill-based soccer-specific exercise protocols**

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

328 \*\*\*INSERT TABLE 3\*\*\*

329 To the authors knowledge, Abt et al.,<sup>68</sup> were the first group to document the development of a treadmill-  
330 based simulation. The total distance covered during the simulation is comparable with match-play<sup>5</sup>, and  
331 the physiological response (heart rate<sup>12</sup> and blood lactate<sup>14</sup>) is consistent with match analyses. However,  
332 the validity of the simulation is questionable, as there exists a low frequency of changes in locomotion  
333 versus match-play data.<sup>34</sup> The authors proposed a solution to simulate outdoor running mechanics,  
334 which involved manipulating a feature of the treadmill design to incorporate changes in both treadmill  
335 speed and gradient. Previous research demonstrates that applying a treadmill gradient of 1% elicits an  
336 energy cost equal to outdoor running at lower speeds, whilst a 2% inclination better reflects high-speed



337 activity ( $18 \text{ km}\cdot\text{h}^{-1}$ ).<sup>69</sup> However, it is unclear whether such alterations to the treadmill gradient  
338 influences running mechanics. Considering that the simulation lasts for 61 min (29-min shorter than a  
339 soccer match), though reaches match distances, the distance at each movement category is likely  
340 excessive, and as such, there are evidently validity issues.

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

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

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

## 374 5. Practical applications and future research directions

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

380 \*\*\*INSERT TABLE 4\*\*\*

381 Considered from a fatigue-management perspective, free-running simulations may be used for highly  
382 specific 'top-up' conditioning work for partial-match players (substitutes/those being replaced)<sup>77, 78</sup> as  
383 opposed to general fitness sessions. Using simulations might offer new avenues for training with  
384 reference to late-stage return-to-play rehabilitation and provide a progressive mechanical strain that  
385 closely duplicates an actual match.<sup>65</sup> Initially, treadmill-based variants may be suitable to preclude

386 change-of-direction elements associated with non-contact loading-related knee injuries.<sup>79</sup> Progressive  
387 loading may then be facilitated by the execution of strenuous utility movements and soccer-specific  
388 tasks associated with free-running simulations.<sup>22</sup> Performing free-running simulations on natural turf  
389 appears appropriate for early rehabilitation to prevent exacerbating residual hamstring fatigue  
390 associated with artificial surfaces<sup>40</sup>, potentially increasing injury-risk. Practitioners examining the  
391 physical capacity of players, instead of replicating match demands, are advised to use the YYIR level  
392 1<sup>80</sup> or level 2 test.<sup>81</sup> Research groups must also be cognisant that assessments merely designed to  
393 measure technical components (Loughborough Soccer Passing and Shooting Tests<sup>82</sup>) cannot be used as  
394 appropriate surrogates for match-play. Indeed, testing fitness and technical components can provide  
395 coaches with objective feedback, including an indication of distinctive strengths and deficiencies.<sup>83</sup>  
396 However, given the acquisition of game skills and the increased energy expenditure of exercising with  
397 the ball<sup>49</sup>, free-running simulations integrating skill components are likely beneficial for preparation for  
398 competition and maintaining technical training stimuli.

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

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

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

436 This article provides a detailed analysis of the individual simulations present within the literature. It is  
437 recommended that researchers consider the critical reflections within the current article and use these

438 as a guide to inform their choice of simulation. For specific considerations of each simulation, readers  
439 are advised to refer to the above sections. However, as general guidance, free-running simulations have  
440 ecologically valid characteristics and should be utilised for studies that are focused on playing  
441 surfaces<sup>40</sup>, technical actions<sup>24</sup> and change-of-direction tasks.<sup>28</sup> Motorised and NMT laboratory-based  
442 simulations possess high experimental control and are efficacious for assessing the influence of the  
443 temperature and altitude on physical performance.<sup>25</sup> These designs also provide a progressive 'real'  
444 match dynamic to facilitate return-to-play, as they do not contain multidirectional movements (e.g.,  
445 twisting and turning).<sup>65</sup> The NMT may be preferred to individualise speed thresholds<sup>51</sup>, whilst the fixed  
446 bouts associated with motorised treadmills eliminates pacing<sup>65</sup> and elicits reliable data.<sup>18</sup> It is advised  
447 that future work validating simulations are designed to imitate the evolving and irregular demands of  
448 match-play. Novel simulations should be geared towards the development of original ideas that simulate  
449 authentic competitive conditions.

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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., <sup>13</sup>	—	Bangsbo <sup>44</sup>	8 university-standard soccer players	2 x 45 min halves with 15 min passive half-time period	9.7 km	6 x 14 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., <sup>47</sup>	Loughborough intermittent shuttle test (LIST)	Reilly <sup>8</sup> Withers <sup>46</sup>	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% $\dot{V}O_{2max}$ , and 3 x 20 m at 95% $\dot{V}O_{2max}$ Part B: Alternate 20m shuttles at 55 and 95% $\dot{V}O_{2max}$ until volitional exhaustion	Unable to be ascertained	Unable to be ascertained	15 m sprint tests
Small et al., <sup>28</sup>	Soccer-specific aerobic field test (SAFT <sup>90</sup> )	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., <sup>41</sup>	—	Reilly <sup>8</sup>	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)	<i>n</i> = 192	Unable to be ascertained	Agility, kicking, dribbling and heading accuracy tests Backwards, sideways and jumping movements
Williams et al., <sup>43</sup>	Ball-sport endurance and sprint test (BEAST <sub>90</sub> )	Withers <sup>46</sup> Mayhew and Wenger <sup>45</sup> Bangsbo <sup>44</sup>	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	<i>n</i> = 903	Unable to be ascertained	Vertical jumps and shooting tasks
Russell et al., <sup>25</sup>	Soccer match simulation (SMS)	Bloomfield et al., <sup>11</sup>	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% $\dot{V}O_{2max}$ , 1 x 20 m backwards jog at 40% $\dot{V}O_{2max}$ , and 2 x high-speed runs completed at 85% of predicted $\dot{V}O_{2max}$ . Following each bout, a 1 min passing test and 1 min passive rest was completed	<i>n</i> = 126	Unable to be ascertained	Dribbling, passing and shooting tasks Backwards jogging

Bendiksen et al., <sup>49</sup>	Copenhagen soccer performance test (CST)	Bangsbo <sup>44</sup> Mohr et al., <sup>2</sup>	12 Danish 2 <sup>nd</sup> and 3 <sup>rd</sup> 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 <sup>-1</sup> ), jogging (171 m; ~8 km·h <sup>-1</sup> ), low (69 m; ~12 km·h <sup>-1</sup> ), moderate (41m; ~15 km·h <sup>-1</sup> ), high-speed running (55m; ~18 km·h <sup>-1</sup> ); sprinting (2 x 20m; ~6 km·h <sup>-1</sup> ), backwards running (30 m; ~8 km·h <sup>-1</sup> ), and backwards or sideways running (20 m; ~8 km·h <sup>-1</sup> ).	Unable to be ascertained	Unable to be ascertained	Dribbling, passing, shooting and heading tasks Backwards and sideways running
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**Note.**  $\dot{V}O_{2\max}$  = Maximal oxygen consumption, PSS = Peak sprint speed

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**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., <sup>57</sup>	—	Drust et al., <sup>57</sup>	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 <sup>-1</sup> ), 3 x walking (4 km·h <sup>-1</sup> ), 3 x jogging (8 km·h <sup>-1</sup> ), 1 x cruising (12 km·h <sup>-1</sup> ) and 1 x sprinting (maximal).	<i>n</i> = 198	Unable to be ascertained	No specific description of pacing was present
Thatcher and Batterham <sup>53</sup>	—	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 (3.64 s x 4; 0 km·h <sup>-1</sup> ), 8 x walking (4.3 s x 4; 5 km·h <sup>-1</sup> ), 7 x jogging (3.58 s x 4; 10 km·h <sup>-1</sup> ), 2 x running (3.82 s x 3; 17 km·h <sup>-1</sup> ) and 1 x sprinting (2.8 s; 23 km·h <sup>-1</sup> )	<i>n</i> = 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., <sup>59</sup>	Soccer-specific intermittent-exercise test (SSIET)	Drust et al., <sup>57</sup>	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 <sup>-1</sup> ), 15 s cruising (12 km·h <sup>-1</sup> ), 15 s stationary, 40 s jogging (8 km·h <sup>-1</sup> ) and a 5 s maximal sprint	<i>n</i> = 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., <sup>51</sup>	The intermittent soccer performance test (iSPT)	Bangsbo <sup>44</sup> Withers <sup>46</sup>	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)	<i>n</i> = 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., <sup>66</sup> <b>Note:</b> PSS = Peak sprint speed	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 <sup>-1</sup> ). High and medium speeds corresponded to 100 and 75 % of an individual's $\dot{V}O_{2\max}$	$n = 27$	13:1	A range of gradients (0—7 %) were applied to the activity profile
Drust et al., <sup>68</sup>	Reilly <sup>8</sup>	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 <sup>-1</sup> ), 6 x jogging (50.3 s; 12 km·h <sup>-1</sup> ), 3 x cruising (51.4 s; 15 km·h <sup>-1</sup> ) and 8 x sprinting (10.5 s; 21 km·h <sup>-1</sup> )	$n = 92$	Unable to be ascertained	Gradient undisclosed
Greig et al., <sup>69</sup>	Bangsbo <sup>70</sup>	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 <sup>-1</sup> ), 55 x walking (6.7 s; 4 km·h <sup>-1</sup> ), 42 x jogging (3.5 s; 8 km·h <sup>-1</sup> ), 46 x low-speed running (3.5 s; 12 km·h <sup>-1</sup> ), 20 x moderate-speed running (2.5 s; 16 km·h <sup>-1</sup> ), 9 x high-speed running (2.1 s; 21 km·h <sup>-1</sup> ) and 3 x sprinting (2.0 s; 25 km·h <sup>-1</sup> )	$n = 894$	5:1	A gradient of 2% was applied to the activity profile throughout
Page et al., <sup>16</sup>	Mohr et al., <sup>2</sup>	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 <sup>-1</sup> ), 65 x walking (6.4 s; 4 km·h <sup>-1</sup> ), 53 x jogging (3.0 s; 8 km·h <sup>-1</sup> ), 48 x low-speed running (2.6 s; 11.6 km·h <sup>-1</sup> ), 17 x moderate-speed running (2.2 s; 15 km·h <sup>-1</sup> ), 12 x high-speed running (2.1 s; 18 km·h <sup>-1</sup> ) and 7 x sprinting (2.5 s; 25 km·h <sup>-1</sup> )	$n = 1386$	3:1	A range of gradients (1—2.5%) were applied to the activity profile

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

<b>Consideration</b>	<b>Free running</b>	<b>Non-motorised treadmill</b>	<b>Motorised treadmill</b>
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
<b>Research and Practical Application</b>			
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
<b>Total</b>	<b>24</b>	<b>18</b>	<b>18</b>

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

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