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1 **Interchangeability of position tracking technologies; can we merge data?**

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10

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21 **Abstract**

22 Purpose: The purpose of this study was to assess the interchangeability of position tracking
23 metrics obtained using global positioning systems (GPS) versus those obtained by a semi-
24 automatic high definition (HD) optical camera system. Methods: Data was collected from a
25 cohort of 29 elite soccer players (age: 23.1 ± 5.1 years, height: 180.4 ± 5.8 cm, mass: $74.6 \pm$
26 6.7 kg) in four matches played in four different stadiums. In two matches 10Hz GPS (GPS-1,
27 StatSports, Belfast, UK) were used, while in the other two matches augmented 10Hz GPS
28 (GPS-2, StatSports, Belfast, UK) were used. All four matches were analysed concomitantly
29 using six semi-automated HD motion cameras sampling at 25Hz (TRACAB, Chyronhago,
30 New York, USA). Results: Mean bias was between 6-10% for GPS-1 and 1-4% for GPS-2
31 respectively. No proportional bias was found ($p > 0.184$). The SEE within calibration
32 functions (expressed in % to mean) was between 5-22% for GPS-1 and 4-14% for GPS-2.
33 While some significant differences existed between GPS-1 and TRACAB (total distance and
34 high-speed), positional tracking variables were highly correlated between GPS-1, GPS-2 and
35 TRACAB ($r^2 > 0.92$) with GPS-2 displaying stronger correlations ($> r^2 = 0.96$). Conclusion:
36 In the present study augmented GPS technology (GPS-2) and the TRACAB camera system
37 provided interchangeable measures of positional tracking metrics to allow concurrent
38 assessment and monitoring of training and competition in soccer players. However, we
39 recommend practitioners evaluate their own systems to identify where errors exist and re-
40 calibrate accordingly to confidently interchange data.

41

42

43 **Introduction**

44 Until recently, the use of global positioning systems (GPS) was prohibited in official
45 competition conditions by FIFA. Despite a law change in 2015, GPS remains under-utilised
46 due to practical reasons such as comfort and player compliance. As such, commercial optical
47 semi-automatic camera systems are still commonly used to track the locomotive patterns of
48 professional players during official match-play. Recently a semi-automated HD optical
49 tracking system known as TRACAB has been installed in every English Premier League
50 stadium and numerous soccer stadiums around the world. Six HD cameras track both the
51 movement of players and the ball, allowing the calculation of the same variables derived
52 from GPS systems, including total distance and distances travelled within specific velocity
53 bands (Cummins et al. 2013).

54 External load metrics such as total distance, high-speed and sprint distance are frequently
55 monitored in high-level professional clubs across many leagues around the world including
56 the English Premier League, La Liga, Serie A, Major League Soccer and Australian A-league
57 (Akenhead and Nassis, 2016). Monitoring changes in these external load metrics that are
58 commonly related to varying demands in training and match-play is used by practitioners to
59 mitigate potential injury risk (Bowen et al. 2019). The application of evidence-based
60 periodised football specific loading strategies (Walker et al. 2018) serves to enhance
61 performance, build chronic load, improve physical qualities and potentially reduces injury
62 risk (Malone et al. 2017; Duhig et al. 2016). A player's retrospective external load data also
63 provides an important benchmark to consider in both the planning and delivery of outdoor
64 physical preparation sessions during rehabilitation and return to play (RTP) (Taberner et al.
65 2018; Blanch and Gabbett, 2016).

66 Surprisingly, limited information currently exists regarding the interchangeability of data
67 derived from contemporary GPS and optical tracking technologies (Buchheit et al. 2014)
68 especially considering how widely used GPS is in professional clubs alongside TRACAB
69 data (Beato et al. 2018a). Without such information practitioners are unable to confidently
70 combine training and match data in order to monitor weekly total volumes, intensities and
71 frequencies of various components of external load. It is important for practitioners to be able
72 to do so to support; 1) training monitoring and prescription to enhance performance, 2)
73 management of load to minimise cumulative fatigue, 3) mitigation of injury risk, and 4)
74 rehabilitation and RTP of injured players (Gabbett, 2016; Gabbett et al. 2017; Bowen et al.
75 2016; Taberner and Cohen 2018).

76 The purpose of this study was to assess the interchangeability between position tracking
77 variables derived from GPS and those of a semi-automatic HD camera system in elite
78 football players.

79 **Methods**

80 ***Participants***

81 A cohort of twenty-nine elite football players from the first team (n = 9 players) and under-23
82 (n = 20 players) squads belonging to an English Premier League soccer club participated (age:
83 23.1 ± 5.1 years, height: 180.4 ± 5.8 cm, mass: 74.6 ± 6.7 kg), with data collected over four
84 matches. For GPS-1 and TRACAB comparison, data was collected from two competitive
85 under-23 matches in the 2016/2017 season. In match one, data was collected from 12 players
86 (age: 21.8 ± 4.6 years, height: 180.4 ± 5.1 cm, mass 73.0 ± 4.5 kg) and in match two from 11
87 players (age: 20.5 ± 0.9 years, height: 181.1 ± 6.1 cm, mass: 71.5 ± 5.3 kg). For the GPS-2 and
88 TRACAB comparison, data was collected from 9 players during one pre-season first team
89 friendly match (age: 27.9 ± 4.4 years, height: 180.4 ± 6.4 cm, mass: 77.4 ± 9.1 kg) and from

90 10 players (age: 20.2 ± 1.4 years, height: 181.3 ± 5.1 cm, mass: 74.3 ± 4.7 kg) during one
91 competitive under-23 match in the 2017/2018 season.

92 All data arose as a condition of employment in which players were routinely monitored over
93 the course of the competitive season. Nevertheless, approval for the study from the club was
94 obtained (Winter and Maughan, 2009) and ethics approval was granted by the University of
95 Santander ethics committee. To ensure confidentiality, all data were anonymised before
96 analysis.

97 ***Experimental overview***

98 Positional information was recorded by two commercially available GPS units; GPS-1 (10Hz
99 Viper, StatSports, Belfast, UK), GPS-2 (augmented 10Hz Apex, StatSports, Belfast, UK) and
100 concomitantly by an optical tracking system using six semi-automated HD cameras sampling
101 at a frequency of 25Hz (TRACAB, Chyronhego, New York, USA). Information regarding
102 both validity and relative reliability of GPS-1 and GPS-2 is available within the literature
103 (Beato et al. 2018a, Beato et al. 2018b, Heidi et al. 2018). For example, GPS-1 has reported a
104 small mean bias ($<5\%$) in the evaluation of distance, sports-specific activity and peak speed
105 (Beato et al. 2018b). More recently GPS-2, a 10Hz multi-GNSS augmented unit capable of
106 acquiring and tracking multiple satellites was validated, with a small error of 1-2% reported
107 compared to a criterion distance of 400m track, a 128.5m sports specific circuit, and peak
108 speed assessed using a gold standard criterion (radar gun) (Beato et al. 2018a). Furthermore,
109 GPS-2 inter-unit reliability was $<2\%$ for components of external load including total distance
110 and high-speed running ($>5\text{ms}^{-1}$) (Heidi et al. 2018).

111 GPS units were positioned between the players' scapulae housed by a specifically designed
112 vest garment used to minimise movement artefacts (Varley et al. 2017) and were activated
113 accordingly to manufacturer's guidelines prior to kick-off. To avoid potential inter-unit

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variation players wore the same GPS unit for each match (Malone et al. 2017). The GPS signal quality and horizontal dilution of position were unavailable for GPS-1. GPS-2 was connected to a mean number of 18 satellites, range 16-20 between the two games, while HDOP for both matches was 1.3 (1st team) and 1.1 respectively (under-23).

Following each match, raw GPS data files and TRACAB files (XML, DAT) were analysed and position variables were derived automatically using the manufacturer's software (Viper and Apex PSA software, StatSports, Belfast, UK). Position tracking variables analysed consisted of total distance, high speed running distance (HSR, >5.5ms⁻¹), and sprint distance (>7ms⁻¹) as defined by the manufacturer¹. These position tracking variables were selected for analysis as they were the top 3 variables monitored by professional clubs in high-level OR "elite" football to quantify training practices and competitive matches (Akenhead and Nassis, 2016). Data were downloaded for analysis using the manufacturer's software, as software-derived data is a more simple and efficient way for practitioners to obtain data in an applied environment, with no differences reported between processing methods (software-derived to raw processed; Heidi et al. 2018). The dwell time (minimum effort duration) was set at 0.5s to detect high speed running and 1s to detect sprint distance efforts; in-line with manufacturers recommended and default settings to maintain consistent data processing (Malone et al. 2017). Furthermore, the internal processing of both GPS-1 and GPS-2 units utilised the Doppler shift method to calculate both distance and velocity data which is shown to display a higher level of precision and less error compared with data calculated via positional differentiation (Townshend et al. 2008).

¹ <http://statsports.com/technology/apex-software/>

137 **Statistical Analysis**

138 Data are presented as mean $\pm$ standard deviation (s). A two-sample Kolmogorov-Smirnov
139 goodness-of-fit hypothesis test was used to check the normality distribution of the data and
140 findings indicated normality in every examined measure ($p > 0.195$).

141 To examine the interchangeability between positional tracking variables derived from the
142 GPS-1, GPS-2 and TRACAB, a Bland-Altman plot and regression analysis were used. The
143 resulting correlation coefficient (Pearson) was used to examine shared variation ($r^2 < .3$
144 small, $.3 < r^2 < .5$ moderate and $r^2 > .5$ large), while the standard error estimate (SEE) as well
145 as the confidence interval (95 and 99%) of the square root of the error from the regression
146 equation was used to assess confidence in the observed values. To evaluate the existence of
147 proportional bias, the percentage difference between the devices was regressed to their
148 average (Bland et al. 1999). In addition to the test of relationship, a two-tailed paired-sample
149 t-test was used to examine differences between devices. Data was analysed using statistical
150 parametric mapping (spm0d version 0.4) and an alpha level of $\alpha = 0.05$ was utilised. Data
151 analysis was performed in MATLAB (The MathWorks, Massachusetts, USA).

152 **Results**

153 All examined measures demonstrated strong positive correlations between both GPS-1, GPS-
154 2 and TRACAB ($r^2 = 0.92$), while, significant differences were observed for total distance
155 and HSR between GPS-1 and TRACAB ($p = 0.00$). GPS-2 displayed the stronger correlation
156 to the TRACAB system ($r^2 > 0.96$ vs. $r^2 > 0.92$). The SEE (expressed in % to mean) was
157 between 5-22% of for GPS-1 and 4-14% for GPS-2. The mean bias was between 6-10% for
158 GPS-1 and 1-4% for GPS-2. No proportional bias was observed ($p > 0.184$). Table 1 and
159 Table 2 report descriptive statistics and analysis for GPS-1 and GPS-2 compared to

160 TRACAB. The Bland-Altman plot and regression analysis alongside correction calibration
161 equations for GPS-1, GPS-2 are displayed in figure 1.

162 **Discussion**

163 Athlete-tracking technology is commonplace in contemporary sport research and practice
164 (Cummins et al. 2013) and it is important that practitioners are able to make confident
165 comparisons if different devices are used in training and competition.

166 In the current study, we examined the interchangeability between data for position tracking
167 variables captured by commercial global positioning systems (GPS) and that derived from a
168 semi-automatic HD camera system (TRACAB). Results showed that while there are
169 differences for both total distance and HSR between GPS-1 and TRACAB, both the GPS-1
170 and GPS-2 were highly correlated with TRACAB ($r^2 > .92$). GPS-1 generally demonstrated
171 higher mean biases compared to GPS-2: total distance (6% vs. 2%), HSR (10% vs. 1%) and
172 sprinting (10% vs. 4%). Furthermore, SEE's ranged from 5-22% for GPS-1 and 4-14% for
173 GPS-2.

174 Due to the current controversy in the sports science world regarding terminology, statistical
175 approaches and interpretation (Impellizzeri et al. 2019), the authors feel it important to clarify
176 the statistical approach used here to assess interchangeability. Agreement was identified
177 through regression analysis - a statistical technique to examine whether, and how strongly, a
178 pair share variation, which is expressed by correlation coefficient "r" (Giavarina, et al. 2015).
179 The regression analysis also computed a relationship formula that allows the prediction of the
180 magnitude of a measure from one device to another. The accuracy of this equation can be
181 described using the SEE (McHugh, 2008). The Bland-Altman analysis provides information
182 about the mean bias (how much does a device over or underestimate the other) as well as the
183 confidence limits of this bias, which explains potential systematic or random error between

184 tracking technologies (Myles and Cui, 2007). As such, a high correlation between devices
185 (representing the mean association) does not necessarily make it appropriate to use in
186 monitoring individual players, if for example there is also a high mean bias. However, a
187 practitioner could use the regression formula to enable align the data obtained with the two
188 systems.

189

190 Previous research investigating interchangeability between GPS and optimal tracking
191 technology (most commonly the Prozone optical tracking system) is limited, with
192 methodological differences accounting for discrepancies in the results reported across studies
193 (Buchheit et al. 2014; Harley et al. 2011; Randers et al. 2010). In agreement with previous
194 findings (Randers et al. 2010), Harley et al. (2011) reported higher total distance travelled
195 using GPS (GPS: $1,755.4 \pm 245.4$ m; Prozone: $1,631.3 \pm 239.5$ m; $p < 0.05$). Harley et al.
196 (2011) emphasised caution in interchanging sprint distance determined by the two
197 technologies due to a technical error of ~40% ($d = 0.68$). More recently, Buchheit et al.
198 (2014) highlighted small differences (5.4%) between GPS and optical tracking systems in
199 relation to total distance covered. The optical tracking technology tended to report greater
200 distance covered at higher movement speeds (>19.8 km/h - 26.5%) with a typical error of
201 estimates that was small (>0.2) to moderate (>0.6) (Buchheit et al. 2014). In contrast, smaller
202 differences were observed in the current investigation in relation to both total distance and
203 distances within high-velocity speeds thresholds. Factors such as device sampling rate,
204 satellite connection, data filtering and analysis within the associated software for both GPS
205 and optical tracking systems (Buchheit et al. 2014) could contribute to the differences
206 between the present results and those of previous reports. As such, caution is required when
207 using GPS units without knowing the quality of satellite connections or if there was a poor
208 satellite connection during a specific data collection period.

209 The present findings show that total distance can be interchanged between augmented 10 Hz
210 GPS (GPS-2) and the TRACAB system with an expected mean error of 4% .. However, it is
211 important to note that HSR and sprinting distance demonstrated larger errors than total
212 distance. Applying corrections through the extrapolation of the Y-intercept demonstrated a
213 SEE of 10% for HSR and 14% for sprinting distance for GPS-2. SEE's were similar for GPS-
214 1 apart from sprinting distance (14% vs 22%). These observed differences are likely due to
215 systematic error with technology used to track positional variables. They may be related to
216 data filtering and/or smoothing of the TRACAB co-ordinate data (X, Y) integrated into GPS
217 analysis software resulting in hysteresis (differences in distance at any measurement value
218 within specified range [speed threshold] recorded using TRACAB compared to raw GPS
219 data). Differences may have also been influenced by measurement error due to loss of
220 satellite connection. As such, the present observations could differ from those in similar
221 future studies due to the prevailing satellite connections, highlighting that data on satellite
222 connection (number of satellites/HDOP) should be included as a time varying covariate
223 within any future GPS study.

224 From a practical perspective, it is important to consider whether the small differences
225 between technologies reported here are meaningful regarding their influence on decisions
226 made/interpretation of data derived from monitoring concurrent loads (training and match-
227 play). Furthermore, meaningfulness and relevance need to be considered, as relationships
228 between running performance and competitive success are unclear (Carling et al. 2013),
229 whilst the impact of training and match-play upon fatigue (Nedelec, 2014) and fitness (Rollo
230 et al. 2014) is likely to be influenced by a host of factors including periodisation, recovery
231 and training methodology, which makes these relationships difficult to examine in an elite
232 environment. In the present study, applying the GPS-2 calibration equations to a sample
233 player's data set (a full-back); TRACAB – total distance: 11,022m, HSR: 1,220m: sprinting:

341m corrected to GPS-2; total distance: 10,730m, HSR: 1,398m, sprinting: 332m) highlights in practice the magnitude of difference in absolute terms (minimal and maximum error; Figure 1)) between GPS-2 and TRACAB; total distance 292m (15 to 355m) from TRACAB, HSR; 37m (13 to 98m) from TRACAB and sprinting; 9m (8 to 18m) from TRACAB. In real-world elite soccer, the question arises as to whether these differences are meaningful in relation to player management in context of both the team performance and/or rehabilitation. Recently, associations between increased acute loads, changes in week-to-week load and injury risk have been demonstrated (Rogalski et al. 2013). Excessive and rapid increases in load are recognised as an important risk factor for non-contact soft-tissue injuries (Gabbett et al. 2016). Therefore, we can ask the question; are the aforementioned absolute differences meaningful in relation to injury risk? Here, ~292m (less than one lap of an athletic track) and in the context of a weekly micro cycle where players typically accumulate distances of around 30 to 40km, an error of + or - this magnitude would not have any practical influence on the interpretation of the data i.e. not have altered decisions regarding player load management. Similarly, in relation to HSR, one of the commonly measured external load metrics related to intensity, should an approximate error of + or - 37m should be considered in the context of a full-back accumulating ~2000 to 2500m HSR within a weekly micro cycle?

It has been advocated that to determine if change in load within individual players is meaningful, the method proposed by Hopkins et al. (2009) should be used to express relative change to intra-player reliability (Akenhead and Nassis, 2016). In team sport environments, these changes (bandwidth determined by Hopkins method) may be used to assess changes in week-to-week loads, variations of the acute: chronic 'workload' ratio e.g. 7 to 28 days, or more sensitive measures e.g. variations to match-day type specific sessions. From a rehabilitation perspective, we suggest that following injury, retrospective external running

259 loads should be used to formulate a prospective return to chronic loading plan (Taberner et al.
260 2019).

261 We observed a lower mean error reported by GPS-2 in comparison to GPS-1, which could be
262 explained by technological enhancements between GPS units. Augmented GPS (GPS-2)
263 utilises a multi-band GNSS receiver capable of acquiring and tracking multiple satellite
264 constellations (e.g. GPS, GLONASS, Galileo, and BeiDou) concurrently, therefore providing
265 more accurate positional data quality (Beato et al. 2018a). Previous research has highlighted
266 that the number of satellites connected to a tracking device plays a pivotal role in GNSS
267 accuracy (Scott et al. 2016) and consequently the enhanced data quality provided by the
268 augmented GPS could explain the lower mean error recorded with TRACAB system
269 compared to GPS-1. Data was also recorded in what could be considered suboptimal
270 conditions due to the experiment being conducted within of high-rise stadiums. Previous
271 research has also reported that satellite pick up near high buildings can affect the validity and
272 reliability of data recorded in such environments (Scott et al. 2016). Hence practitioners
273 should interpret all data with caution in stadia and ensure raw traces of velocity and
274 acceleration are inspected for irregularities generated by the GPS devices, which may include
275 satellite signal loss leading to a delayed detection of locomotion (Malone et al. 2017).
276 Accounting for the satellite connection and horizontal dilution of position would allow the
277 development of formulas that could state when it is 'safe' to interchange or could give a
278 range of possible magnitude for different signal strength to help practitioners fully establish
279 interaction between all components of external load. We suggest professional clubs should do
280 their own diligence investing time and resources to assess their own systems, checking for
281 potential sources of error to ascertain confidence in their dataset when concurrently
282 monitoring training and match data.

283 Alongside total distance and distance within high velocities (HSR and sprinting), external
284 load in team sports is also characterised by frequent episodes of accelerated and decelerated
285 running actions (Osgnach et al. 2010). Hence, monitoring the demands that require athletes to
286 accelerate, decelerate and rapidly change direction is of high importance (Delaney et al.
287 2017). As by definition a proportion of these movements are performed at low speed and
288 despite being below the threshold for HSR ($>5.5\text{ms}^{-1}$), have a high mechanical demand with
289 important implications for planning training and recovery strategies (Osgnach et al. 2010;
290 Young et al. 2012). We suggest future research should aim to establish interchangeability
291 between acceleration, deceleration variables recorded by GPS and optical tracking
292 technologies, considering the number of satellites as a time dependent covariate, to help
293 practitioners fully establish interaction between all components of external running load.

294 **Conclusion**

295 The interchangeability between training and match load data is important to help practitioners
296 effectively and confidently monitor and interpret weekly volume of external running loads.
297 Current findings demonstrate that data can be interchanged between the present augmented
298 GPS units and TRACAB system with an expected mean error of 4%, which we estimate to
299 have no practical influence on the interpretation of weekly load data. Since the present
300 commercial GPS and TRACAB systems are used ubiquitously within professional soccer
301 clubs these findings will help enable practitioners to combine training (captured using GPS)
302 and match activity (captured using optical systems) data, to assist with planning of
303 appropriate training and recovery strategies to impact physical performance and potentially
304 reduce injury risk.

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446 Table 1. Relationships between GPS-1/TracAb for Total distance, High-speed distance, and
447 Sprint distance.

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449 Table 2. Relationships between GPS-2/TracAb for Total distance, High-speed distance, and
450 Sprint distance.

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452 Figure 1. Correlations between GPS-1/TracAb and GPS-2/TracAb for Total distance, High-
453 speed distance, and Sprint distance.

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