MUSCLE DAMAGE–BASED RECOVERY STRATEGIES CAN BE SUPPORTED BY PREDICTIVE CAPACITY OF SPECIFIC GLOBAL POSITIONING SYSTEM ACCELEROMETRY PARAMETERS IMMEDIATELY A POST-SOCCER MATCH-LOAD

Cristiano D. da Silva,1,2 Guilherme Machado,3 Alex Andrade Fernandes,4 Israel Teoldo,3 Eduardo M. Pimenta,2 João C. B. Marins,5 and Emerson S. Garcia6

1Department of Physical Education, Institute of Life Sciences, Federal University of Juiz de Fora, Governador Valadares, Minas Gerais, Brazil; 2School of Physical Education, Physiotherapy and Occupational Therapy, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil; 3Department of Physical Education, Center of Research and Studies in Soccer, Federal University of Viçosa, Viçosa, Minas Gerais, Brazil; 4Federal Institute for Education, Science and Technology of Minas Gerais, Governador Valadares, Minas Gerais, Brazil; 5Department of Physical Education, Human Performance Laboratory, Federal University of Viçosa, Viçosa, Minas Gerais, Brazil; and 6Department of Physical Education, Federal University of Maranhão, Maranhão, Brazil

Abstract
da Silva, CD, Machado, G, Fernandes, AA, Teoldo, I, Pimenta, EM, Marins, JCB, and Garcia, ES. Muscle damage–based recovery strategies can be supported by predictive capacity of specific global positioning system accelerometry parameters immediately after soccer match-load. J Strength Cond Res XX (X): 000–000, 2018—Soccer match-load can be linked to recovery kinetic markers. However, match variability hinders the magnitude of relationship between parameters of interest. Therefore, we examined the correlation between 21 global positioning system accelerometry (GPS-A) parameters and changes in serum creatine kinase (CK) concentrations, muscle soreness (MS), and perceptive recovery quality (PRQ) as-assessed at baseline (1 h before) and post (0 minute, 2, 4, and 24 hours) a standardized 90-minute match-simulation in 12 university players. Global positioning system accelerometry (15 Hz) data were tested as manufacturer and configurable thresholds. Four GPS-A parameters showed moderate to very large correlations with CK changes at all time points (average speed [avgSP], r = 0.75 to r = 0.84; running symmetry foot strikes [RSfst], r = 0.53–0.63; running series [RunS], r = 0.53–0.61; and acceleration distance [AccD r = 1.5 m·s−2; r = 0.46–0.61]). Sprint count (≥2 m·s−2), AccD (≥2.5 m·s−2) and speed exertion (SpEx) had a moderate to large correlation (r = 0.46–0.56) with CK changes from 2 to 24 hours. Changes in MS at 0 minute had large correlation with avgSP (r = 0.53) and moderate with deceleration distance (≥−2 and ≥−3 m·s−2; r = 0.47, r = 0.48, respectively). The PRQ changes had moderate inverse correlation with avgSP at 0 minute (r = −0.39) and SpEx at 2 h (r = −0.69). Our results suggest that during a simulated soccer protocol with a standard workload, only the avgSP has practical application for predicting CK changes over 24 hours, allowing for a decision-making toward a postgame recovery based on previously known CK cutoff points. Global positioning system accelerometry parameters and subjective variables did not demonstrate relevant correlation.

Key Words external load, prediction, athlete management, time-motion analysis, fatigue

Introduction

time-motion analysis using wearable tracking devices with global positioning system (GPS), micro-electrical mechanical system gyroscopes, magnetometers, and accelerometers in single-unit components is now commonplace in sport research and practice (26). These devices provide large amounts of external load data regarding total distance (TD) covered, type of movement, amount of physical contact, tackles, count and distance on acceleration, and deceleration performed by players. These derived physical performance parameters can be used to lead the decision-making of athlete training direction by measuring the external load (8,26), playing tactics, and team interactions
Based on an applied perspective, the quality and time of the athlete’s recovery may be associated with the magnitude of muscle damage and soreness following a match-play, and therefore it may be interesting to establish a valid predictive monitoring tool based on more sensitive variables and threshold configurations and in GPS accelerometry (GPS-A)–based metrics to know the need for recovery of an athlete, as soon as possible. Therefore, the correlation or predictive metrics between internal load and physical performance from match-play may be important for the control of player load adaptation and recovery status (18,34,36). The magnitude of postmatch responses seems to be correlated with the performed activity profile (18).

It was hypothesized that activities with a high-intensity and eccentric component as commonly observed in a soccer match-load would be associated with large changes in muscle damage markers, subjective pain, and impaired perceived quality of recovery. For example, previous knowledge of the creatine kinase (CK) baseline coupled with external load information through GPS-A data could be useful for decision-making and thereby to optimize athletes’ recovery interventions and muscle injury prevention procedures.

Despite this potential utility, only a few studies have described GPS-A–derived parameters (GPS-A_par) and their relationship to this muscle damage marker. For example, Russell et al. (34) examined 15 professional soccer players over 1–4 matches and reported a correlation between distance covered at velocities >5.5 m·s⁻¹ and the number of sprints per minute (>4.4 m·s⁻¹) with changes in CK at 24 hours (r = 0.38 and 0.41, respectively). However, no relationships were observed between any GPS variables and changes in CK after 48 hours of recovery. In another study analyzing 15 young soccer players with the same GPS recorded at 10 Hz, Hoyo et al. (12) found significant correlations between changes in CK and distance covered at velocities ≥21 km·h⁻¹ at 24 hours (r = 0.56) and at 48 hours (r = 0.54), as well as correlations between this marker and distance covered >14 km·h⁻¹ (r = 0.50), and events in acceleration (>3 m·s⁻², r = 0.48), and deceleration (>2 m·s⁻², r = 0.58). However, despite the ecological validity of the studies cited above, the practical significance of the correlations presented should be interpreted with caution because of the small sample size used (i.e., 15 players), low number of matches, and fragile experimental context (e.g., environmental factors, hydration practices, and tactics influence), which are inherent to competitive environment.

The competitive game scenario and its large match-load interindividual variability weaken the reliability of responses and consequently could discourage the use of GPS-derived parameters for predictive capacity in internal load metrics or recovery management markers. Moreover, the aforementioned soccer studies (12,34,36) only focused on predicting muscle damage marker responses. Therefore, decision-making for monitoring subjective muscle soreness (MS) and perceptive recovery quality (PRQ) status should also be considered. Thus, the use of GPS-A and its selected parameters and thresholds is really advantageous to use for profiling fatigue and as a recuperative control of athletes through link with muscle damage markers, soreness, subjective recovery quality, and readiness to train are still unclear.

To our knowledge, there are currently no reports on relationships between specific GPS-A_par–derived time-motion metrics, its thresholds and CK, MS, and PRQ in a more controlled before and during soccer match-demand experimental situation. Therefore, the aim of the current study was to evaluate the relationships between 21 specific GPS-A_par using manufactured and particular threshold measures and changes in CK, MS, and PRQ in a recovery period of up to 24 hours. This experimental model also proposed to standardize preintervention feeding, hydration, and match-load, which enables us to determine any uncoupling in mechanical loading response to a game-related physical load protocol. This investigation approach could maximize the opportunity to predict immediate postmatch-relevant marker changes from a series of GPS-A_par and separate those, which are most important in recovery athlete management.

**Method**

**Experimental Approach to the Problem**

A within-player observational study design with 5 repeated measures was implemented. Although competitive team-sport matches present the most ecologically valid modality to assess match-play load responses, workload distribution and experimental control are compromised. Moreover, monitoring valuable postmatch load variable is compromised by competitive logistics such as travel and lodging. Hence, an experimental scenario was assembled with individual standardization before, during, and after a full 90-minute soccer match-simulation protocol (SMP; an adapted version of SAFT90 (24); for more details check descriptive section of this procedure).

Subjects reported to the laboratory on 3 different occasions. On the first visit, the sample was characterized anthropometrically and evaluated for their dietary habits to be used in the prescription of the pretrial meal. The subjects were also familiarized with SMP. The SMP was used to overcome match-to-match variability in workload distribution. Inferences have been made that GPS-A may be unable to detect changes when devices are harnessed in the trunk higher than upper-body kinematics, greatly influencing the distribution of accumulated load in each motion vector (plane) (4,5). The device movement and those dependent on its fitting within the athlete’s garment and anatomical location could therefore compromise the suggested changes in acceleration metrics and corresponding changes in lower-limb stiffness (6,26).
Participants were asked to avoid intense physical activity for 24 hours before the experimental session. On the second visit, subjects performed a control test, which consisted of a standardized meal, hydration, warm-up and stretching, and soccer-demand protocol. Blood sample (i.e., CK, MS, and PRQ) states were assessed 1 hour before (baseline), immediately (0 minute), at 2 hours, and at 4 hours after SMP. These same measurements were performed during the third visit after 24 hours after SMP. We then evaluated the change (Δ; from baseline) in these markers and analyzed the relationship with 21 GPS-A parameters (GPS-A <sub>pa</sub>).

**Subjects**
Twenty (21) male university-standard outfield soccer players (mean ± SD [minimum–maximum]; age = 23 ± 2 years [20–27 years]; height = 175 ± 5 cm [169–186]; body mass = 74 ± 10 kg [66–94]) of various positional roles (defense, midfield, and attack) volunteered to participate in the study. The local ethics committee of the university approved the study, and subjects were informed of the risks and benefits before any data collection. Written informed consent was obtained according to the Helsinki declaration. The study was approved by the Research Ethics Committee of the Federal University of Minas Gerais. Subjects had finished their competitive season of University Athletic League approximately 2 weeks before the study started but were still engaged in unstructured training to maintain fitness. Exclusion criteria included use of medications, use of dietary supplements, and being injured and ill in last month before starting the study, or having problems reported during the study.

**Procedures**
Eating habits (AVANUTRI 4.0; Três Rios/RJ, Brazil), compliance, body mass (Welmy W200/5, São Paulo, Brazil), height (Sanny Standard, São Paulo, Brazil), and estimated percent body fat (skinfold caliper Cescorf, Brazil) (19) were collected by the same researcher. These data also served for sample characterization and dietary breakfast meal prescription in the experimental session. Participants were asked to record their diet for 72 hours before the trial and for the remainder of the trial day after their session. In the experimental session, each subject arrived at the laboratory (06:00 AM) after an 8 hours overnight fast (water was allowed) and having abstained from caffeine, alcohol, and high-intensity exercise for a minimum of 24 hours. Immediately after arriving at the laboratory, the subjects were invited to empty their bladder and provide a spot urine sample (50 ml) used to ascertain pre-exercise hydration status according to urine specific gravity (USG). Subjects then consumed 5 ml·kg<sup>−1</sup> body mass (BM) of water (39). Three participants remained hypohydrated (USG ≥ 1.020 arbitrary unit) (10), and so an additional 2 ml·kg<sup>−1</sup> of water was consumed (39).

A pre-exercise meal was standardized to meet estimate energy requirements of 18% energy for each participant (approximately 380 kcal, 68 g of CHO, 11 g of PRO, and 7 g of FAT). The subjects performed 15 minutes of standard soccer warm-up and stretching before starting the SMP. Aiming for ecological validity because of similarities with difficulties and insufficient rehydration in soccer match-play, hydration during SMP was programmed for safety and exercise comfort. Scheduled individual water supply (2 ml·kg<sup>−1</sup> BM) occurred every 15 minutes up to 75 minutes after a methodological approach (27,35). Subjects were instructed to not wet their heads, or spit any water out.

Soccer-demand protocol activities were recorded using a conventional and widely used GPS-A device (SPI ProX; GPSports, Canberra, Australia). The subjects provided a rating of perceived exertion (RPE) using Borg’s (7) category ratio scale immediately after the first and second half of the SMP. Subjects also used the Polar Team System device unit to record heart rate (HR). Peak HR values observed in training, familiarization with SMP or in the trial was used for effort intensity calculation (HRpeak%). A standardized meal with vegetables, rice, meat, and beans for high carbohydrate ingestion (1.2 g·kg<sup>−1</sup> BM) and fluid replacement after exercise (150% of the body mass lost) with water was served ~45 minutes after SMP. No additional recovery strategy (e.g., ice baths, compression garments, hydrotherapy, and exercise) was used.

**Soccer Match–Simulation Protocol.** An adapted version based on SAFT<sup>90</sup> (two 45-minute halves with 15 minutes of rest) fatiguing exercise protocol was used as SMP to reflect soccer match-play load from audio command (24). To extend specific application of SAFT<sup>90</sup> to make it more sensitive to physiological and mechanical soccer activity demands, technical skills such as ball dribbling (12 times, total 240 m), short passes (24 times), shots on target (12 times) (9,31), and jumps (12 times; positioned barrier [30 cm]) (13) were integrated alongside displacement course matched with competitive game event loads without decharacterizing frequency, order, or the rhythm of original activities. We followed the strategy used in the original protocol and to keep experimental control of workload, and therefore, the study eliminated physical impact of contact situations as well as player’s interactions for ball disputes such as tackling or heading.

The self-selected locomotor speeds when necessary strategy was implemented with the aim for the players to use conscious or subconscious pacing strategies to enable physical and technical performance (14), adherence to longer exercise, and to reflect the between-half differences as in real match-play. The expected activity profile consisted of 1,332 changes in direction and 1,269 changes in speed. The SMP were performed on a natural turf pitch with 25 ± 1°C and 63 ± 1% RH.

**Measurements: Global Positioning System/Accelerometry.** Amotion Date Parameters and Threshold Analysis. A GPS-A device sampled participant location with 15-Hz satellite-based measurement system, and a 100-Hz integrated accelerometer (GPSports, SPI-Pro, Canberra, Australia) was used. The reliability and accuracy of this GPS-A device have been
GPS-A Parameters as Internal Load Predictive Tool

primary_text

<table>
<thead>
<tr>
<th>TABLE 1. Main time-motion parameters and internal load indices of standardized soccer match-play simulation.*†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load variables</td>
</tr>
<tr>
<td>TD (m)</td>
</tr>
<tr>
<td>avgSP (km·h⁻¹)</td>
</tr>
<tr>
<td>HSD ≥14.4 km·h⁻¹</td>
</tr>
<tr>
<td>VHSD ≥20 km·h⁻¹</td>
</tr>
<tr>
<td>LSD &lt;14.4 km·h⁻¹</td>
</tr>
<tr>
<td>Maximum speed (km·h⁻¹)</td>
</tr>
<tr>
<td>RPE₆₋₂₀ AU</td>
</tr>
<tr>
<td>HRpeak%</td>
</tr>
</tbody>
</table>

*TD = total distance; avgSP = average speed; HSD = high-speed distance; VHSD = very high-speed distance; LSD = low-speed distance; RPE = rating of perceived exertion in arbitrary unit—a.u.; HRpeak% = heart rate peak percentage; m = meters; p-value obtained from the Wilcoxon test; mean difference = considering the magnitude of within-trial standardized difference; effect size (ES) from g (unbiased estimate of Cohen’s d) [90% confidence intervals, CI].
†Results are given as mean ± SD.

previously reported (21). A GPS-A unit was fitted to the upper back of each player using an elastic harness. The sensor location was chosen to maximize the validity of the recordings without hiding the athlete’s body center to ensure a sufficient connection and to minimize disturbances to the player during activity. Global positioning system accelerometry was switched on and placed outdoors 15 minutes before starting the warm-up. The average ±SD number of satellites and horizontal dilution of position during the trial were 15.0 ± 0.2 and 0.74 ± 0.01, respectively. These values have been suggestive of being acceptable for good GPS-A signal coverage based on the manufacturer’s recommendations (26).

After match-simulation, the raw data files were analyzed and 21 GPS-Apar of physical performance derived from various running speeds, acceleration, and deceleration distance (AccD and DecD, respectively), and mechanical foot strikes were automatically derived by Team AMS (version R1 2014.3; GPSports, SPI Elite, Australia) software in standard changes in direction and speed). For the current study proposal, only g force data of <5.0 to 6.0 (light collision impact) were considered but nevertheless counts for acceleration, deceleration, and changes in direction while running were retained for analysis. To distinguish between acceleration movements where subjects speed-up vs. slowdown, the term “deceleration” is used to describe a decreasing rate of change in velocity. Minimum effort duration criteria of 0.8 seconds was implemented to prevent brief thoracic movements from registering as locomotive efforts, but acceleration data were not smoothed in any way. Athlete running mechanics and changes in their mechanics were analyzed through key parameters such as “running imbalance SD” (%RIsd, % difference between left and right foot strikes) and “running symmetry foot strikes” (%RSfst; number of foot strikes and number of series of foot strikes in sequence combined with settings to control for change in direction and speed).

Creatine Kinase, Muscle Soreness, and Perceived Recovery Quality Measurement. Measurements occurred before (1 hour) and immediately (0 minute) after SMP and according to the subsequent monitoring timeline (2, 4, and 24 hours). Serum CK concentration change (delta) was used as muscle damage marker. An 8-ml SST Gel Vacutainer tube was used to collect blood to measure the CK serum level. Samples were centrifuged (Labofuge 400; Kendro Laboratory Products, Hanau, Germany) at 3,400 rpm for 10 minutes. Serum samples were then stored at −80°C before subsequently being analyzed for CK using BS 2,200 (Bioclin) using kit analyzers (Quibasa Quı́mica Básica Ltd, Belo Horizonte, Brazil). Samples were measured in duplicate (3% coefficient of variation) and recorded as mean values. Subjects were asked to complete a self-reported questionnaire that assessed their rated feelings about MS by adopting a 10-cm visual analogue scale ranging from 0 “normal” to 10 “extremely

Copyright © 2018 National Strength and Conditioning Association
sore” (15), and using a PRQ scale ranging from 0 “extremely tired” to 10 “very well recovered” (23).

**Statistical Analyses**

All data were first square root-transformed to reduce bias arising from nonuniformity error. All results are presented as original units of absolute mean values ± SDs. Mean values derived from the analysis of transformed variables were back-transformed to provide the fold change relative to baseline values. Wilcoxon test was used for comparisons between each 2 time-points of interest. The effect size (ES ± 90% confidence intervals) of $g$ (unbiased estimate of Cohen’s $d$) was calculated to quantify the magnitude of mean difference. The magnitude of criteria range for mean difference was: 0–0.2, trivial; >0.2–0.6, small; >0.6–1.2, moderate; >1.2–2, large; >2, very large; and >4.0, extremely large (16). Pearson’s correlation coefficient ($r$) was used to assess the correlation between 21 GPS-A parameters and changes in CK, MS, and PRQ. The criteria adopted to categorize magnitude of correlation between these aforementioned measures were ≤0.1, trivial; >0.1–0.3, small; >0.3–0.5, moderate; >0.5–0.7, large; >0.7–0.9, very large; and >0.9–1.0, almost perfect (16). The a priori level of practical significance of the $r$ coefficient was set to 0.70 or greater. All statistical analyzes were performed by IBM SPSS 21 for Windows (Chicago, IL, USA). Statistical significance was set at $p ≤ 0.05$.

**RESULTS**

**Time-Motion Parameters and Internal Load Indices of Soccer Match Simulation**

Table 1 outlines the main time-motion results of $TD$, $AvgSP$, distances covered in various defined speed, and internal load indices (RPE and HRpeak%) from first and second half. The mean $TD$ covered during the SMP was 10.029 ± 673 m with 85 ± 6% HRpeak. Half changes were classified as small to large ES range magnitude (Table 1).

Mean baseline CK values were 157 ± 202 U·L$^{-1}$. Substantially, greater CK changes were shown at 0 minute (2-fold [317 ± 202 U·L$^{-1}$]; ES = 2.25 [1.58, 2.93]). The CK continued to increase with a large increase at 2 hours (2.3-

---

### Table 2. Pearson’s product of moment correlation coefficients ($r$) between global positioning system accelerometry (GPS-A) parameters and changes in CK, MS, and PRQ after standardized soccer match-play simulation.*†

<table>
<thead>
<tr>
<th>GPS accelerometer parameters</th>
<th>$\Delta$CK (%)</th>
<th>$\Delta$MS (%)</th>
<th>PRQ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 min</td>
<td>2-h</td>
<td>4-h</td>
</tr>
<tr>
<td>TD (m)</td>
<td>0.39</td>
<td>0.40</td>
<td>0.43</td>
</tr>
<tr>
<td>LSD &lt;14.4 km·h$^{-1}$ (m)</td>
<td>0.18</td>
<td>0.12</td>
<td>0.06</td>
</tr>
<tr>
<td>HSD ≥14 km·h$^{-1}$ (m)</td>
<td>0.09</td>
<td>0.13</td>
<td>0.18</td>
</tr>
<tr>
<td>VHS &lt;20 km·h$^{-1}$ (m)</td>
<td>0.19</td>
<td>0.28</td>
<td>0.36</td>
</tr>
<tr>
<td>VHS &gt;20 km·h$^{-1}$ (m)</td>
<td>0.07</td>
<td>0.11</td>
<td>0.15</td>
</tr>
<tr>
<td>AvgSP</td>
<td>0.75</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>SpEx</td>
<td>0.36</td>
<td>0.39</td>
<td>0.46</td>
</tr>
<tr>
<td>Sprint count ≥2 m·s$^{-2}$</td>
<td>0.33</td>
<td>0.42</td>
<td>0.50</td>
</tr>
<tr>
<td>AccD ≥1 m·s$^{-2}$ (m)</td>
<td>0.18</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>AccD ≥1.5 m·s$^{-2}$ (m)</td>
<td>0.45</td>
<td>0.46</td>
<td>0.51</td>
</tr>
<tr>
<td>AccD ≥2 m·s$^{-2}$ (m)</td>
<td>0.04</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>AccD ≥2.5 m·s$^{-2}$ (m)</td>
<td>0.31</td>
<td>0.41</td>
<td>0.48</td>
</tr>
<tr>
<td>AccD ≥3 m·s$^{-2}$ (m)</td>
<td>0.01</td>
<td>0.10</td>
<td>0.14</td>
</tr>
<tr>
<td>AccD ≥3.5 m·s$^{-2}$ (m)</td>
<td>0.30</td>
<td>0.37</td>
<td>0.44</td>
</tr>
<tr>
<td>DecD ≥2 m·s$^{-2}$ (m)</td>
<td>0.38</td>
<td>0.42</td>
<td>0.44</td>
</tr>
<tr>
<td>DecD ≥3 m·s$^{-2}$ (m)</td>
<td>0.29</td>
<td>0.38</td>
<td>0.41</td>
</tr>
<tr>
<td>DecD ≥4 m·s$^{-2}$ (m)</td>
<td>0.32</td>
<td>0.33</td>
<td>0.36</td>
</tr>
<tr>
<td>DecD ≥5 m·s$^{-2}$ (m)</td>
<td>0.44</td>
<td>0.45</td>
<td>0.49</td>
</tr>
<tr>
<td>RunS</td>
<td>0.53</td>
<td>0.52</td>
<td>0.54</td>
</tr>
<tr>
<td>Rdsl</td>
<td>0.25</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>RSft</td>
<td>0.53</td>
<td>0.53</td>
<td>0.56</td>
</tr>
</tbody>
</table>

*CK = creatine kinase concentration; MS = muscle soreness; PRQ = perceptive recovery quality; AvgSP = average speed; TD = total distance; LSD = low-speed distance; HSD = high-speed distance; VHS = very high-speed distance; SpEx = speed exertion; AccD = acceleration distance; DecD = deceleration distance; RunS = running series; Rdsl = running imbalance standard deviation; RSft = running symmetry foot-strike.

† Indicates significant correlation at $p < 0.001$ level.
§ Indicates significant correlation at $p < 0.05$ level.
fold [371 ± 274 U·L⁻¹]; ES = 2.10 [1.44, 2.75]) and 4 hours (2.8-fold [455 ± 411 U·L⁻¹]; ES = 1.95 [1.31, 2.59]) after SMP. The highest observed CK change occurred at 24 hours (3.2-fold [660 ± 752 U·L⁻¹]; ES = 1.36 [0.77, 1.94]). Mean baseline MS values were 0.3 ± 0.6 cm. The MS had very large increased values at 0 minute (4.6-fold [5.15 ± 1.9 cm]; ES = 3.11 [2.32, 3.89]). Subjects remained with MS with a large increase at 2 hours (2.6-fold [2.6 ± 1.5 cm]; ES = 1.80 [1.18, 2.42]) and at 4 hours (2-fold [1.74 ± 1.1 cm]; ES = 1.65 [1.04, 2.26]) and a very large increase at 24 hours (2.1-fold [1.75 ± 0.7 cm]; ES = 2.41 [1.72, 3.11]) after SMP.

Mean baseline PRQ values were 9.2 ± 1 a.u. PRQ had the lowest large decrease in values at 0 minute (3.8-fold [2.7 ± 1.9 a.u.]; ES = 2.09 [1.43, 2.74]). Subjects remained with MS with a moderate decrease at 2 hours (2.1-fold [6.8 ± 2.2 a.u.]; ES = 1.12 [0.55, 1.68]) and at 4 hours (1.9-fold [7.13 ± 1.9 a.u.]; ES = 1.02 [0.46, 1.57]) after SMP. Perceptive recovery quality decreased outcome change was only small at 24 hours (0.6-fold [1.75 ± 0.7 cm]; ES = 0.31 [−0.21, 0.84]) after SMP.

### Relationship Between Global Positioning System

#### Accelerometry Time-Motion Parameters and Creatine Kinase

The relationships observed from 21 GPS-A parameters demonstrate that workload at avgSPD, running mechanics, and some AccD and DecD in particular thresholds most importantly correlate with CK changes (Table 2). The avgSPD and RSfit parameters correlated more important with all CK changes in time points (very large \( r = 0.75–0.84 \)) and large \( r = 0.53–0.63 \), respectively, Table 2).

### Relationship Between Global Positioning System

#### Accelerometry Time-Motion Parameters and Muscle Pain

The avgSPD parameters correlated with changes in MS at 0 minute (large \( r = 0.53 \)). Changes in MS at 0 minute also moderately correlated with DecD (\( r = 0.47 \) and \( r = 0.48, \geq -2 \text{ m·s}^{-2} \) or \( \leq -3 \text{ m·s}^{-2} \), respectively, Table 2). The PRQ changes only had moderate significant inverse relationships with avgSPD at 0 minute (\( r = -0.39 \), and with SpEx at 2 h (\( r = -0.69 \), Table 2).

### DISCUSSION

The aim of the current study was to evaluate the relationships between 21 GPS-A parameters using manufactured and particular thresholds of physical performance in a soccer match-play mimicked demands and changes in CK concentration, and in MS and PRQ response up to a recovery period of 24 hours. Our results showed large to very large correlations between average speed (avgSPD), running mechanics (RSfit), running series (RunS), and CK concentration changes in all time points of a 24-hour period. It was also hypothesized that subjective measures could be a valuable tool for player recovery management from some predictive variables of the GPS-A equipment. However, only MS correlated with avgSP and with TD covered in moderate to high deceleration threshold (\( \geq -2 \text{ m·s}^{-2} \) or \( \leq -3 \text{ m·s}^{-2} \)) at one or another measurement point. The PRQ only showed a significant correlation at one time point with avgSPD (0 minute) and SpEx (2 hours).

Any short-term predictive ability of CK concentration after workload is important to make more specific decisions for profiling fatigue and acute recovery practices. The first 2 days after the game is critical, and usually, the athlete is "off" from activities at the club. In this sense, some strategies can be elaborated as soon as the match-play or training is over and the GPS-A data is processed. The prediction of CK concentration from physical load metrics as highlighted by our results may allow practitioners to establish more objective criteria for required recovery intervention when designing the estimated value with those already known from the individual cutoff points. Relationships between CK changes and time-motion parameters from soccer match-play have been reported in literature. Specifically, our results and these collective study’s findings highlight that CK changes could be predicted from high-speed running variables derived from GPS. For example, our findings agree with those of Thorpe and Sunderland (36) who found very large correlations between sprint number (\( r = 0.86 \)), sprint distance (\( r = 0.89 \)), high-intensity distance covered (\( > 15 \text{ km·h}^{-1} \); \( r = 0.92 \)), and CK changes immediately after match in professional soccer matches. Despite these interesting magnitudes of correlations, the small sample and low device sensitivity (1-Hz capacity) are worth noting, which could put limitations on these findings for practical significance.

Agreeing with our findings, Hoy et al. (12) found correlations between distance covered at velocities \( \geq 21 \text{ km·h}^{-1} \) and CK change at 24 hours (\( r = 0.56 \)) and 48 hours (\( r = 0.54 \)), and correlations between CK change and distance covered \( > 14 \text{ km·h}^{-1} \) (\( r = 0.50 \)) in analyzing U-19 elite male players with data recorded at 10 Hz. They also observed correlations between CK change and AccD (\( r = 0.48 \)), and Dec (\( r = 0.58 \), however, at a later time-point in relation to our study (i.e., 48 hours). Russell et al. (34), assessed English Premier League substitute players and also observed a relationship between high-intensity distance covered (\( > 5.5 \text{ km·h}^{-1} \), high-speed running distance (19.8–25.1 km·h⁻¹), and number of sprints per minutes (\( > 25.1 \text{ km·h}^{-1} \) with CK change (\( r = 0.39; 0.36, \) and 0.41, respectively) at 24 hours when another manufactured GPS device with 10-Hz data was used. However, as in our study, Russell et al. (34) only noticed statistically significant correlations between total number of high-intensity accelerations and decelerations and CK change. It should be noted that these results were not confirmed at the 48-hour measurement.

In Australian Rules football players, Young et al. (40) observed that CK changes in higher responders in 24 hours after match only showed a large to very large positive correlation with distances covered running at 14.4–21.6 km·h⁻¹ (\( r = 0.60 \)) and high acceleration of 3–15 m·s⁻² (\( r = 0.75 \)) using similar thresholds to those in our study. Unlike our
study (where $avgSP$ was the only one with practical significance), Young et al. (40) only observed moderate correlations ($r = 0.39$) for this parameter. In soccer, the match-load is different and the body contact experienced degree is considerably less than in Australian Rules football or rugby, which likely explains the lack of any similarity in our results. Moreover, Russel et al. (34) perhaps reported a lack of any impact variables to correlate with CK change, whereas this has traditionally been shown in Rugby (22).

Changes in direction and particularly deceleration movements involving intense eccentric contractions of various muscle groups (40) are known to induce larger alterations in muscle damage, as indicated by increased plasma CK (28). Traditionally, peak CK concentration is observed from 24 to 48 hours with probable concomitant muscle pain disturbances experienced in postmatch recovery. The time course of peak CK observed responses at 24 hours of $660 \pm 572$ U·L$^{-1}$ is perhaps slightly higher because we studied college athletes, but it is consistent with other studies (3,18,25).

Moreover, we found moderate to large correlations between distance covered in high acceleration and deceleration thresholds and CK changes. However, this observed correlation had a more important magnitude in the later phase of the recovery period. The extent of mechanical damage remains unclear over longer periods of recovery and thus warrants further investigation. Methodological differences and equipment, embedded technology, or software manufacturers’ (CatapultSports, GPSports and STATSports for example) indices, filtering, and metrics also limit a more detailed comparison. Also, there is contrasting evidence between players running metrics and muscle damage and neuromuscular performance when the observation was at 48 hours after a match (12).

Our short course time of measurements may also explain the weak or absence of observed correlations for subjective responses of MS and PRQ. Thus, when interpreting the current findings, it should be noted that this study implemented a standardized soccer match simulation, and this could eliminate greater variability of open demands as observed in an official competitive match, which could reflect in more important subjective responses. From the point of view of the physical demands can be stated that there was correspondence with an official match-play. For example, the volume and intensity of running performed, as well as peak and mean HR in SMP, were similar or slightly greater than midfielders during competitive soccer matches (30,32). Similarly, reductions in $TD$, $HSD$, and $VHSD$ variables during the second half compared with first half of SMP were also similar to those reported in match-play (32). However, factors such as physical collisions and ball contact may also contribute to potential neuromuscular system perturbations as reported during and after match (18). Thus, this may reflect in a higher CK response and larger alterations in subjective metrics regarding pain when a real competitive soccer context is considered.

Despite the aforementioned match-play simulation limitation, it is noticed that our attempt for controlling load showed that when the mechanical action loads are fixed, the $avgSP$ parameter had very large correlation with CK change. This might be important information because demands related to average displacement velocity are more stable in real match-play (17,37). Hence, this new information could be relevant, especially if we consider greater intravariability measures related to changes in direction and its GPS-device measurement accuracy when real match-play was measured (2). Thus, another debatable aspect of our results is that they were obtained with stable devices provided by the noncontact standardized 90-minute soccer match-play simulation. For example, Barret et al. (6) observed that individual planes are reliable measures during SMP test-retest reliability, and the anatomical location of the devices is important (scapulae and near the mass center). In this way, specific speed-related ($avgSP$ and $RunS$) parameters and changes in running mechanics ($RSfst$) could be used in the early stage to predict CK response.

Despite all the findings presented, it should be noted that only the $avgSP$ parameter had a practical application (i.e., $r > 0.7$) to predict change in CK concentration at any time up to 24 hours. Routines of analysis considering the different possibilities of CK cutoff point expression can be used (e.g., the absolute values; relative to the maximum concentration [%$CK_{max}$]; and relative to the maximum variation delta [%$\Delta CK_{max}$]) (11). Thus, any CK-based strategy used for monitoring and readiness to train may be established without relying on invasive measures or while awaiting processing and results. Extended data for a season may provide increasingly robust predictive tools.

A number of limitations should be considered for our study. For example, the presented variable correlations were determined using a university sample and should therefore be interpreted with caution because of different recovery abilities. The application of such information is likely limited to the first 24 hours after match-play, and physiological/biochemical variables assessed in later phase (i.e., 48–72 hours) of recovery may not reflect relationships between these indices, as observed more immediately after match in this study.

For costly practical reasons, we were also not able to examine the influence of different filtering techniques within the GPS manufacturers’ software or other updated versions. The GPS-Apar device used was 15 Hz. However, practitioners should be aware of the technology they have available because low sample rate devices have limitations for consistently measuring the distances covered during high-velocity $RunS$, acceleration running over short distances, and velocity measures, especially when changes in direction are performed (17). Furthermore, the distance covered during acceleration and deceleration events may have varied according to movement intensity or manufactured speed, accelerometer thresholds, sampling rates, chip sets, filtering
methods, and data processing algorithms (26). Hence, selection of absolute (or arbitrary) speeds thresholds, and times for the minimum duration, referred to as “dwell time” or minimum effort duration (38) to examine locomotor profile of an activity bout is at the discretion of the user/researcher and informed by the particular population being assessed (26). Future research should also consider the angle of any changes in direction that may accompany acceleration and deceleration events to effectively train change of direction ability.

Improvement in real-time technology could bring even more evidence-based decision-making to practitioners and sports scientists for predicting athletes’ fatigue, muscle damage, mechanical running disturbance, and injury risk. The implementation and predictive success among GPS-A parameters of interest to optimize load management strategies may assume greater importance over time. Otherwise, an injury may occur because of fixture congestion or environmental stressors resulting from a discrepancy between load and recovery.

**Practical Applications**

This study provides a comprehensive account of the relationship between external (GPS-A parameters) and internal (muscle damage through CK response and perceptual measurements—MS and PRQ) load from soccer demands using a self-paced match simulation. We show that muscle damage through CK marker in players was predicted in the context by high-speed running metrics from GPS (i.e., avgSP, RSfit, and Run50) and distance covered in acceleration (≥1.5 m·s⁻²) in the most immediate postmatch period (0 hour). Predictions of change in perceptual measurements (MS and PRQ) were not presented as being of practical application because of the poor correlations with the GPS-A parameters adopted in this study. Findings may be important for conditioning professionals. For example, CK cutoff value-based recovery strategies can be quickly established (practitioners can establish individual equations or group predictions during the season from the best external load metrics) through specific predictive GPS-A-derived indices such as soccer players average speed presented in match-play context. This predictive strategy may be an additional method for decision-making and monitoring directions for profiling the fatigue and recovery process of athletes while waiting for direct and peak CK response from 24 to 48 hours. These new findings can serve as examples of the predictive usefulness of every day commonly used wearable tracking devices and thereby establish strategies to monitor performance, fatigue, recovery, and establish injury prevention strategies of an official competitive scenario.

**Acknowledgments**

This study was financed in part by the Coordination of Improvement of Higher Level Personnel - Brazil (CAPES) - Finance Code 001. It was also partly funded by the State Department of Sport of Minas Gerais (SEESP- MG) through the State Act of Incentive to Sports, by FAPEMIG, CNPQ, FUNARBE, the Dean’s Office for Graduate and Research Studies and the Center of Life and Health Sciences from the Federal University of Viçosa, Brazil.

**References**


