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# Sweat Characteristics of Cramp-Prone and Cramp-Resistant Athletes

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Exercise-associated muscle cramps (EAMCs) are thought to be caused by dehydration and/or electrolyte losses. In this multicenter, cross-sectional study, the authors determined whether sweat rates (SRs), sweat electrolyte concentrations, or sweat electrolyte content differed in athletes with (i.e., crampers) and without (i.e., noncrampers) a history of EAMCs and whether these variables could predict EAMC-prone athletes. Male and female collegiate athletes ($N = 350$) from 11 sports with ($n = 245$) and without ($n = 105$) a self-reported history of EAMCs completed a typical exercise or conditioning session. SRs, calculated from body mass, and posterior forearm sweat were analyzed for sweat sodium concentration ($[Na^+]_{sw}$), sweat potassium concentration ($[K^+]_{sw}$), and sweat chloride concentration ($[Cl^-]_{sw}$). The authors used SRs and sweat electrolyte concentrations to calculate sweat electrolyte content lost. Within each gender, no differences in SRs (204 males, $p = .92$; 146 females, $p = .24$); $[Na^+]_{sw}$ (191 males, $p = .55$; 126 females, $p = .55$); $Na^+_{sw}$ content (191 males, $p = .59$; 126 females, $p = .20$); $[K^+]_{sw}$ (192 males, $p = .57$; 126 females, $p = .87$); $K^+_{sw}$ content (192 males, $p = .49$; 126 females, $p = .03$); $[Cl^-]_{sw}$ (192 males, $p = .94$; 77 females, $p = .57$); and $Cl^-_{sw}$ content (192 males, $p = .55$; 77 females, $p = .34$) occurred between crampers and noncrampers. Receiver operating characteristic curve analysis revealed that sweat electrolyte content and SRs were predictive of EAMC-prone athletes in American football (area under curve = 0.65–0.72, $p \le .005$), but not in any other sport. EAMCs may not be solely caused by fluid or electrolyte losses in most athletes. Fluid and electrolyte replacement may help American footballers. Clinicians should individualize fluid and electrolyte replacement and understand different etiologies for EAMCs.

***Keywords****:* chloride, dehydration, electrolytes, potassium, sodium

Exercise-associated muscle cramps (EAMCs) compose a significant proportion of exertional heat illnesses, particularly in American football (Cooper et al., 2006). Numerous factors contribute to EAMC genesis (Bergeron, 2008; Casa et al., 2015; Miller, 2018; Schwellnus, 2009). Dehydration and electrolyte losses are the most popular assumed causative factors (Stone et al., 2003). The dehydration/electrolyte theory states that sweating contracts the extracellular fluid space increasing the concentration of excitatory neurochemicals and mechanical pressure on motor nerve terminals (Bergeron, 2008).

The dehydration/electrolyte theory is often supported by observational research (Bergeron, 1996, 2003; Moss, 1923) or research comparing sweat losses and sweat electrolyte concentrations in athletes with or without EAMC histories (Horswill et al., 2009; Stofan et al., 2005). Many studies associate EAMCs with fluid, sodium ($Na^+$), potassium ($K^+$), or chloride ($Cl^-$) losses because of their importance in fluid balance, muscle contraction, and nerve conduction. Sweat losses, whether matched or unmatched by fluid or dietary intake, may result in hypohydration, acute or chronic fluid and electrolyte deficits, and other disorders (Fowkes-Godek et al., 2010; Noakes, 1998; Osterberg et al., 2009; Volpe et al., 2009).

Many studies (Bergeron, 1996; Horswill et al., 2009; Stofan et al., 2005) examining EAMCs and sweat losses only tested one gender and observed discrepant findings (Horswill et al., 2009; Stofan et al., 2005). This raised questions regarding the ability of sweat rates (SRs) or sweat electrolyte concentrations to predict EAMCs. Our study determined if differences in SRs and sweat electrolyte variables existed in athletes with and without EAMCs, if these sweat variables could predict EAMC history, and quantified sweat characteristics of several sports. We hypothesized sweat losses would be higher in cramp-prone athletes, these variables would be capable of identifying cramp-prone athletes, and sweat losses would be different across gender and sports.

## Methods

### Participants

We estimated sample size using prior data (Horswill et al., 2009; Stofan et al., 2005) and the following assumptions: alpha level of .01, 80% power, $[Na^+]_{sw}$ differences of 22 mmol/L, and *SD*s of 13 mmol/L. We needed seven subjects per group to detect differences.

Three hundred and fifty Division 1 college athletes (204 males, age = 20 ± 1 y; height = 186.4 ± 8.6 cm; mass = 96.7 ± 21.8 kg and

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146 females, age = 19 ± 1 y; height = 170.1 ± 9.4 cm; mass = 69.6 ± 10.8 kg) completed this multicenter, cross-sectional study. Athletes came from 18 teams, 11 sports, and four universities. Volunteers were excluded if they had any injuries, any neurological or cardiovascular disease, or were taking medications known to influence fluid balance or temperature regulation. All procedures were approved by our ethics boards; volunteers consented before participating.

## Procedures

Athletes answered a questionnaire and investigators attended a scheduled practice or conditioning session based on coach permission. Preexercise body mass assessment occurred 15–20 min before each session. Sweat patches were applied just before exercise onset. Athletes and coaches were instructed to conduct their exercise session (duration: 30–120 min) as normal. During exercise, researchers recorded ambient temperature and relative humidity near the playing field. Athletes drink ad libitum (including beverage choice) during exercise. Postexercise, athletes dried themselves completely and body mass was measured within 10 min.

## Instruments and Measurements

***Baseline questionnaire.*** Demographic information and EAMC history (categorical: yes and no) was self-reported. We asked "Have you ever had a muscle cramp, heat cramp, or charley horse during or after exercise?" EAMCs were clarified as involuntary, painful contractions of skeletal muscle during or after exercise (Schwellnus, 2009). This definition was provided at the beginning of each questionnaire and verbally reviewed by researchers to ensure menstrual, gastrointestinal, and nocturnal cramps or other types of muscle injuries (e.g., strains) were not misguiding EAMC reporting.

***Sweat rate.*** Athletes emptied their bladders before body mass assessment. Men wore shorts and women wore shorts and sports bras. Body mass was recorded to 0.1 kg precision (Defender #5000; Ohaus Corporation, Parsippany, NJ; Health-o-meter #349KLX; Health O Meter Inc., Bedford Heights, OH; #TBF 300A; Tanita Corp., Arlington Heights, IL). Athletes drank from preweighed/measured, individual water bottles. After practice/exercise, athletes dried themselves completely before body mass assessment. Remaining fluids were measured to the nearest 1 ml or 0.1 g. Gross SR was calculated using the formula: SR = [(pre body mass − post body mass) − urine produced + fluid ingested]/exercise duration (McDermott et al., 2017) though no urine was produced in any of the testing sessions.

***Sweat electrolyte procedures and analysis.*** If necessary, athletes shaved their forearms before patch adhesion. All forearms were cleaned with alcohol and deionized water, and wiped clean with a lint-free wipe. Sterile gauze covered in occlusive dressing and was placed on the posterior mid-forearms (Baker, 2017). After 30–40 min of exercise (for consistency between data collection sites), or when researchers determined saturation, sweat patches were removed. Researchers wore gloves to avoid contamination. Sweat patches were placed in clean test tubes and centrifuged for 10 min at 4,500*g* and 3 °C. Extracted sweat was transferred to a clean 1.5-ml tube and analyzed using ion-selective electrodes, in duplicate, for $[Na^+]_{sw}$, $[K^+]_{sw}$, and sweat chloride concentration ($[Cl^-]_{sw}$; NOVA 5; Nova Biomedical Corp., Waltham, MA; Easy-Lyte; Medica Corp., Bedford, MA). $[Na^+]_{sw}$ and $[K^+]_{sw}$ were corrected to account for regional patch collection (Baker et al., 2009). Gross SR was multiplied by corrected sweat electrolyte concentrations to determine content losses. Intersite electrolyte analyzer reliability of preliminary samples ($n = 40$) was excellent (intraclass correlation coefficient ≥ .8).

## Statistical Analyses

Descriptive statistics were calculated for all dependent variables. Gross SR was recorded and normalized using body surface area ($SR_{BSA}$; Mosteller, 1987). We compared sweat characteristics by gender and EAMC history using 2 × 2 analyses of variance. "Sport" was not included as a third factor in our modeling because we did not have data from both genders for each sport. Then, we separated the data by gender and used 2 × 2 analyses of variance to determine if differences existed between sports and EAMC history. Tukey–Kramer post hoc tests followed significant *F* values.

We also analyzed the data using clinically relevant statistics. Receiver operator characteristic curve analysis identified area under curve and significant prediction based on Fisher's exact test ($p < .01$). Subsequently, cut point values for variables were determined based on adequate balance between sensitivity and 1-specificity in the software-generated coordinate chart. Then, we dichotomized athletes as a 1 (*elevated risk*) or 0 (*no risk*) based on established cut points for specific variables, and completed crosstab analysis to determine sensitivity, specificity, and diagnostic odds ratios. To protect against Type I errors, significance was accepted when $p < .01$ (version 2007; NCSS; Kaysville, UT).

# Results

Data are presented as mean ± *SD*. Subject demographics, environmental conditions, activity types and locations, SR, and $SR_{BSA}$ data are presented in Table 1.

## Gender and EAMC History Results

We did not observe an interaction between EAMC history and gender for $[Na^+]_{sw}$, $F(1, 313) = 0.02$, $p = .88$, $Na^+_{sw}$ content, $F(1, 307) = 2.03$, $p = .16$, $[K^+]_{sw}$, $F(1, 314) = 0.75$, $p = .39$, $K^+_{sw}$ content, $F(1, 308) = 2.73$, $p = .09$, $[Cl^-]_{sw}$, $F(1, 265) = 0.60$, $p = .44$, $Cl^-_{sw}$ content, $F(1, 264) = 1.59$, $p = .21$, $SR_{BSA}$, $F(1, 346) = 0.44$, $p = .51$, or SR, $F(1, 346) = 0.83$, $p = .36$. We did not observe a main effect for "EAMC history" for $[Na^+]_{sw}$, $F(1, 313) = 2.28$, $p = .13$, $Na^+_{sw}$ content, $F(1, 307) = 5.12$, $p = .02$, $[K^+]_{sw}$, $F(1, 314) = 1.67$, $p = .19$, $K^+_{sw}$ content, $F(1, 308) = 5.56$, $p = .02$, $[Cl^-]_{sw}$, $F(1, 265) = 0.29$, $p = .59$, $Cl^-_{sw}$ content, $F(1, 264) = 3.45$, $p = .06$, $SR_{BSA}$, $F(1, 346) = 1.11$, $p = .29$, or SR, $F(1, 346) = 1.74$, $p = .19$. We observed differences between genders for $[Na^+]_{sw}$, $F(1, 313) = 34.89$, $p < .001$, $Na^+_{sw}$ content, $F(1, 307) = 14.49$, $p < .001$, $[K^+]_{sw}$, $F(1, 314) = 112.89$, $p < .001$, $K^+_{sw}$ content, $F(1, 308) = 12.43$, $p < .001$, $[Cl^-]_{sw}$, $F(1, 265) = 7.79$, $p = .005$, $Cl^-_{sw}$ content, $F(1, 264) = 20.47$, $p < .001$, $SR_{BSA}$, $F(1, 346) = 27.23$, $p < .001$, and SR, $F(1, 346) = 67.62$, $p < .001$. Males lost more fluid and electrolytes than females (Tables 1 and 2).

## Male Sports and EAMC History Results

We did not observe an interaction between "EAMC history and sport" for $[Na^+]_{sw}$, $F(4, 181) = 0.46$, $p = .76$, $Na^+_{sw}$ content, $F(4, 180) = 1.82$, $p = .13$, $[K^+]_{sw}$, $F(4, 182) = 0.56$, $p = .69$, $K^+_{sw}$ content, $F(4, 180) = 1.60$, $p = .18$, $[Cl^-]_{sw}$, $F(4, 182) = 0.44$, $p = .78$, $Cl^-_{sw}$ content, $F(4, 181) = 1.75$, $p = .14$, $SR_{BSA}$, $F(4, 194) = 1.06$,

**Table 1 SR, Testing Conditions, and Anthropometrics of Athletes With and Without a Self-Reported Lifetime History of EAMCs**

| Sport | Sample size ($n$) | BMI (kg/m$^2$) | BSA (m$^2$) | SR (L/hr) | SR/BSA (L·hr$^{-1}$·m$^{-2}$) | Activity type | $T_{amb}$ (°C) and rH (%) |
|---|---|---|---|---|---|---|---|
| Male sports | | | | | | | |
| American football | | | | | | | |
| EAMC history | 83 | 30.9 ± 4.9 | 2.34 ± 0.26 | 1.57 ± 0.53 | 0.67 ± 0.19 | Off-season aerobic conditioning (indoors) and practice (outdoors) | 22 ± 5 and 38 ± 17 |
| Control | 27 | 28.6 ± 3.8 | 2.24 ± 0.19 | 1.29 ± 0.42 | 0.57 ± 0.15 | | |
| Aggregate[a] | 110 | 30.4 ± 4.8 | 2.32 ± 0.25 | 1.50 ± 0.52 | 0.64 ± 0.19 | | |
| Baseball | | | | | | | |
| EAMC history | 12 | 26.6 ± 1.9 | 2.15 ± 0.18 | 1.23 ± 0.27 | 0.57 ± 0.11 | In-season aerobic conditioning (indoors) | 22 and 29 |
| Control | 5 | 24.8 ± 2.8 | 2.10 ± 0.19 | 1.40 ± 0.24 | 0.67 ± 0.12 | | |
| Aggregate[a] | 17 | 26.1 ± 2.3 | 2.14 ± 0.18 | 1.28 ± 0.27 | 0.60 ± 0.12 | | |
| Basketball | | | | | | | |
| EAMC history | 24 | 23.4 ± 1.2 | 2.14 ± 0.17 | 0.86 ± 0.45 | 0.39 ± 0.18 | In-season practice (indoors) and off-season aerobic conditioning (indoors) | 20 ± 3 and 28 ± 12 |
| Control | 7 | 25.3 ± 2.8 | 2.33 ± 0.16 | 1.19 ± 0.74 | 0.51 ± 0.29 | | |
| Aggregate[a] | 31 | 23.8 ± 1.8 | 2.18 ± 0.18 | 0.94 ± 0.53 | 0.42 ± 0.21 | | |
| Track and field | | | | | | | |
| EAMC history | 23 | 23.2 ± 3.7 | 2.01 ± 0.14 | 1.68 ± 0.95 | 0.84 ± 0.49 | Off-season practice (outdoors) | 27 ± 3 and 43 ± 10 |
| Control | 5 | 21.3 ± 1.2 | 1.89 ± 0.17 | 1.54 ± 0.79 | 0.79 ± 0.36 | | |
| Aggregate[a] | 28 | 22.8 ± 3.4 | 1.99 ± 0.15 | 1.66 ± 0.92 | 0.83 ± 0.47 | | |
| Wrestling | | | | | | | |
| EAMC history | 11 | 25.8 ± 2.5 | 1.98 ± 0.18 | 1.24 ± 0.43 | 0.62 ± 0.18 | Off-season aerobic conditioning (indoors) | 22 and 33 |
| Control | 7 | 27.2 ± 5.3 | 2.00 ± 0.29 | 1.11 ± 0.28 | 0.55 ± 0.07 | | |
| Aggregate[a] | 18 | 26.3 ± 3.7 | 1.99 ± 0.22 | 1.19 ± 0.37 | 0.59 ± 0.15 | | |
| Female sports | | | | | | | |
| Basketball | | | | | | | |
| EAMC history | 20 | 23.8 ± 1.9 | 1.91 ± 0.13 | 0.89 ± 0.53 | 0.46 ± 0.27 | In-season practice (indoors) and off-season aerobic conditioning (indoors) | 24 ± 1 and 46 ± 17 |
| Control | 16 | 24.4 ± 3.5 | 2.00 ± 0.21 | 1.14 ± 0.53 | 0.57 ± 0.28 | | |
| Aggregate[a] | 36 | 24.1 ± 2.7 | 1.95 ± 0.18 | 1.00 ± 0.53 | 0.51 ± 0.27 | | |
| Field hockey | | | | | | | |
| EAMC history | 12 | 22.8 ± 1.4 | 1.74 ± 0.09 | 0.92 ± 0.16 | 0.53 ± 0.09 | Off-season aerobic conditioning (indoors) | 20 and 25 |
| Control | 6 | 22.3 ± 1.6 | 1.63 ± 0.08 | 0.93 ± 0.10 | 0.57 ± 0.05 | | |
| Aggregate[a] | 18 | 22.7 ± 1.5 | 1.69 ± 0.10 | 0.92 ± 0.14 | 0.54 ± 0.08 | | |
| Gymnastics | | | | | | | |
| EAMC history | 6 | 23.1 ± 0.9 | 1.61 ± 0.09 | 0.57 ± 0.08 | 0.35 ± 0.04 | Off-season aerobic conditioning (indoors) | 21 and 46 |
| Control | 4 | 24.1 ± 1.5 | 1.64 ± 0.06 | 0.60 ± 0.16 | 0.36 ± 0.09 | | |
| Aggregate[a] | 10 | 23.5 ± 1.3 | 1.62 ± 0.08 | 0.58 ± 0.11 | 0.36 ± 0.06 | | |
| Soccer | | | | | | | |
| EAMC history | 25 | 22.8 ± 2.1 | 1.75 ± 0.12 | 0.97 ± 0.56 | 0.54 ± 0.28 | Off-season aerobic conditioning (indoors) and in-season practice (outdoors) | 21 ± 5 and 31 ± 8 |
| Control | 11 | 22.2 ± 1.4 | 1.69 ± 0.10 | 0.79 ± 0.31 | 0.46 ± 0.18 | | |
| Aggregate[a] | 36 | 22.7 ± 1.9 | 1.74 ± 0.12 | 0.91 ± 0.49 | 0.52 ± 0.26 | | |
| Softball | | | | | | | |
| EAMC history | 14 | 27.4 ± 3.6 | 1.91 ± 0.14 | 0.79 ± 0.19 | 0.42 ± 0.09 | Off-season aerobic conditioning (indoors) | 32 and 40 |
| Control | 8 | 23.7 ± 2.0 | 1.75 ± 0.14 | 0.68 ± 0.15 | 0.39 ± 0.06 | | |
| Aggregate[a] | 22 | 26.1 ± 3.6 | 1.85 ± 0.16 | 0.75 ± 0.18 | 0.41 ± 0.08 | | |

*(continued)*

**Table 1 (continued)**

| Sport | Sample size (*n*) | BMI (kg/m$^2$) | BSA (m$^2$) | SR (L/hr) | SR/BSA (L·hr$^{-1}$·m$^{-2}$) | Activity type | $T_{amb}$ (°C) and rH (%) |
|---|---|---|---|---|---|---|---|
| Tennis | | | | | | | |
| EAMC history | 5 | 23.4 ± 2.1 | 1.68 ± 0.11 | 1.02 ± 0.31 | 0.61 ± 0.16 | Off-season practice (outdoors) | 28 and 60 |
| Control | 4 | 22.8 ± 2.7 | 1.59 ± 0.09 | 0.49 ± 0.24 | 0.31 ± 0.14 | | |
| Aggregate[a] | 9 | 23.1 ± 2.3 | 1.64 ± 0.11 | 0.79 ± 0.38 | 0.47 ± 0.21 | | |
| Volleyball | | | | | | | |
| EAMC history | 10 | 24.2 ± 3.4 | 1.89 ± 0.13 | 0.54 ± 0.23 | 0.29 ± 0.11 | In-season aerobic conditioning (indoors) and in-season practice (indoors) | 22 ± 1 and 35 ± 22 |
| Control | 5 | 22.5 ± 1.9 | 1.89 ± 0.08 | 0.47 ± 0.18 | 0.25 ± 0.10 | | |
| Aggregate[a] | 15 | 23.6 ± 3.1 | 1.89 ± 0.11 | 0.52 ± 0.21 | 0.28 ± 0.10 | | |
| Aggregates | | | | | | | |
| Gender | | | | | | | |
| Males | 204 | 27.6 ± 5.1 | 2.21 ± 0.26 | 1.39 ± 0.61[b] | 0.63 ± 0.27[b] | Varied | 23 ± 3 and 34 ± 6 |
| Females | 146 | 23.7 ± 2.7 | 1.80 ± 0.17 | 0.84 ± 0.42 | 0.47 ± 0.21 | | 24 ± 4 and 40 ± 12 |
| EAMC history | | | | | | | |
| EAMC history | 245 | 26.4 ± 4.9 | 2.07 ± 0.30 | 1.21 ± 0.63 | 0.58 ± 0.27 | Varied | Varied |
| Control | 105 | 25.0 ± 3.9 | 1.98 ± 0.29 | 1.05 ± 0.50 | 0.52 ± 0.21 | | |
| Gender, EAMC history | | | | | | | |
| Males, EAMC history | 153 | 27.9 ± 5.3 | 2.22 ± 0.26 | 1.43 ± 0.64 | 0.64 ± 0.28 | Varied | Varied |
| Males, control | 51 | 26.9 ± 4.3 | 2.17 ± 0.24 | 1.29 ± 0.48 | 0.59 ± 0.20 | | |
| Females, EAMC history | 92 | 23.9 ± 2.8 | 1.81 ± 0.15 | 0.85 ± 0.42 | 0.47 ± 0.22 | | |
| Females, control | 54 | 23.3 ± 2.5 | 1.80 ± 0.21 | 0.83 ± 0.41 | 0.46 ± 0.21 | | |

*Note*. Data are presented as mean ± *SD*. BMI = body mass index; BSA = body surface area; EAMC = exercise-associated muscle cramping; rH = relative humidity at time of testing; $T_{amb}$ = ambient temperature at time of testing; SR = sweat rate.
[a]Average for all athletes in each sport. [b]Males significantly higher than females ($p < .01$).

$p = .38$, or SR, $F(4, 194) = 1.53$, $p = .19$. We did not observe a main effect for "EAMC history" for $[Na^+]_{sw}$, $F(1, 181) = 0.36$, $p = .55$, $Na^+_{sw}$ content, $F(1, 180) = 0.30$, $p = .59$, $[K^+]_{sw}$, $F(1, 182) = 0.33$, $p = .57$, $K^+_{sw}$ content, $F(1, 180) = 0.46$, $p = .49$, $[Cl^-]_{sw}$, $F(1, 182) = 0.01$, $p = .94$, $Cl^-_{sw}$ content, $F(1, 181) = 0.36$, $p = .55$, $SR_{BSA}$, $F(1, 194) = 0.01$, $p = .96$, or SR, $F(1, 194) = 0.01$, $p = .92$. We observed differences between sports for $[Na^+]_{sw}$, $F(4, 181) = 3.86$, $p = .004$, $[K^+]_{sw}$, $F(4, 182) = 12.65$, $p < .001$, $K^+_{sw}$ content, $F(4, 180) = 4.14$, $p = .003$, $[Cl^-]_{sw}$, $F(4, 182) = 4.46$, $p = .001$, $SR_{BSA}$, $F(4, 194) = 5.26$, $p < .001$, or SR, $F(4, 194) = 3.51$, $p = .009$ (Table 3). No differences between sports was observed for $Na^+_{sw}$ content, $F(4, 180) = 3.31$, $p = .012$, and $Cl^-_{sw}$ content, $F(4, 181) = 3.05$, $p = .02$.

## Female Sports and EAMC History Results

We did not observe an interaction between "EAMC history and sport" for $[Na^+]_{sw}$, $F(6, 112) = 1.15$, $p = .34$, $Na^+_{sw}$ content, $F(6, 107) = 1.72$, $p = .12$, $[K^+]_{sw}$, $F(6, 112) = 1.48$, $p = .19$, $K^+_{sw}$ content, $F(6, 108) = 1.90$, $p = .09$, $[Cl^-]_{sw}$, $F(5, 65) = 0.97$, $p = .44$, $Cl^-_{sw}$ content, $F(5, 65) = 0.97$, $p = .44$, $SR_{BSA}$, $F(6, 132) = 1.50$, $p = .18$, or SR, $F(6, 132) = 1.62$, $p = .15$. We did not observe a main effect for "EAMC history" for $[Na^+]_{sw}$, $F(1, 112) = 0.36$, $p = .55$, $Na^+_{sw}$ content, $F(1, 107) = 1.70$, $p = .19$, $[K^+]_{sw}$, $F(1, 112) = 0.03$, $p = .87$, $K^+_{sw}$ content, $F(1, 108) = 4.99$, $p = .03$, $[Cl^-]_{sw}$, $F(1, 65) = 0.33$, $p = .57$, $Cl^-_{sw}$ content, $F(1, 65) = 0.91$, $p = .34$, $SR_{BSA}$, $F(1, 132) = 1.09$, $p = .29$, or SR, $F(1, 132) = 1.37$, $p = .24$. We observed differences between sports for $[Na^+]_{sw}$, $F(6, 112) = 4.02$, $p = .001$, $Na^+_{sw}$ content, $F(6, 107) = 7.63$, $p < .001$, $K^+_{sw}$ content, $F(6, 108) = 20.60$, $p < .001$, $SR_{BSA}$, $F(6, 132) = 3.94$, $p = .001$, or SR, $F(6, 132) = 3.85$, $p = .001$ (Table 4). No differences were observed for $[K^+]_{sw}$, $F(6, 112) = 2.00$, $p = .07$, $[Cl^-]_{sw}$, $F(5, 65) = 1.47$, $p = .21$, and $Cl^-_{sw}$ content, $F(5, 65) = 1.27$, $p = .29$.

## ROC Analysis

When all data were analyzed, only $Na^+_{sw}$ content, $K^+_{sw}$ content, and $Cl^-_{sw}$ content were predictive of EAMC history (Table 5). Further analysis revealed significant observations were due to American football. When American football data were removed, no sweat variable was predictive of EAMCs in male or female sports.

# Discussion

Contrary to the dehydration/electrolyte imbalance theory (Bergeron, 2008) and our hypothesis, cramp-prone athletes did not lose more sweat or electrolytes than noncrampers. Our data are in contrast to other field studies examining sweat characteristics in crampers (Bergeron, 1996, 2003; Horswill et al., 2009; Stofan et al., 2005).

**Table 2 Sweat Electrolyte Concentrations of Athletes With and Without a Self-Reported History of EAMCs**

| Sport | Sample size for $[Na^+]_{sw}$ (*n*) | $[Na^+]_{sw}$ (mmol/L) | $Na^+_{sw}$ content (g) | Sample size for $[K^+]_{sw}$ (*n*) | $[K^+]_{sw}$ (mmol/L) | $K^+_{sw}$ content (g) | Sample size for $[Cl^-]_{sw}$ (*n*) | $[Cl^-]_{sw}$ (mmol/L) | $Cl^-_{sw}$ content (g) |
|---|---|---|---|---|---|---|---|---|---|
| Male sports | | | | | | | | | |
| American football | | | | | | | | | |
| EAMC history | 74 | 44 ± 13 | 1.6 ± 1.2 | 74 | 5.6 ± 1.2 | 0.4 ± 0.40 | 74 | 53 ± 19 | 3.2 ± 2.6 |
| Control | 23 | 47 ± 11 | 0.9 ± 0.7 | 24 | 6.1 ± 1.6 | 0.2 ± 0.20 | 24 | 53 ± 16 | 1.7 ± 1.4 |
| Aggregate[a] | 97 | 45 ± 13 | 1.5 ± 1.1 | 98 | 5.7 ± 1.3 | 0.4 ± 0.40 | 98 | 53 ± 19 | 2.8 ± 2.5 |
| Baseball | | | | | | | | | |
| EAMC history | 12 | 43 ± 5 | 0.6 ± 0.2 | 12 | 4.7 ± 1.1 | 0.12 ± 0.04 | 12 | 49 ± 9 | 1.1 ± 0.3 |
| Control | 5 | 50 ± 11 | 0.8 ± 0.3 | 5 | 4.4 ± 0.7 | 0.12 ± 0.04 | 5 | 61 ± 20 | 1.6 ± 0.7 |
| Aggregate[a] | 17 | 45 ± 8 | 0.7 ± 0.2 | 17 | 4.6 ± 0.9 | 0.12 ± 0.04 | 17 | 52 ± 13 | 1.2 ± 0.5 |
| Basketball | | | | | | | | | |
| EAMC history | 25 | 51 ± 12 | 1.1 ± 0.4 | 25 | 4.2 ± 0.6 | 0.15 ± 0.04 | 25 | 61 ± 19 | 1.9 ± 0.8 |
| Control | 7 | 49 ± 12 | 1.0 ± 0.3 | 7 | 4.1 ± 0.4 | 0.15 ± 0.04 | 7 | 58 ± 20 | 1.9 ± 0.7 |
| Aggregate[a] | 32 | 50 ± 12 | 1.1 ± 0.3 | 32 | 4.2 ± 0.5 | 0.15 ± 0.04 | 32 | 60 ± 19 | 1.9 ± 0.8 |
| Track and field | | | | | | | | | |
| EAMC history | 23 | 33 ± 5 | 0.7 ± 0.3 | 23 | 4.5 ± 1.3 | 0.17 ± 0.09 | 23 | 35 ± 24 | 1.1 ± 0.6 |
| Control | 4 | 34 ± 3 | 0.8 ± 0.3 | 4 | 4.9 ± 1.1 | 0.21 ± 0.08 | 4 | 32 ± 12 | 1.2 ± 0.7 |
| Aggregate[a] | 27 | 34 ± 14 | 0.7 ± 0.3 | 27 | 4.5 ± 1.3 | 0.17 ± 0.09 | 27 | 34 ± 22 | 1.1 ± 0.6 |
| Wrestling | | | | | | | | | |
| EAMC history | 11 | 48 ± 11 | 0.7 ± 0.3 | 11 | 4.7 ± 0.9 | 0.11 ± 0.04 | 11 | 58 ± 18 | 1.3 ± 0.7 |
| Control | 7 | 46 ± 10 | 0.6 ± 0.2 | 7 | 4.8 ± 0.7 | 0.10 ± 0.02 | 7 | 55 ± 19 | 1.1 ± 0.5 |
| Aggregate[a] | 18 | 47 ± 10 | 0.7 ± 0.3 | 18 | 4.7 ± 0.8 | 0.11 ± 0.03 | 18 | 57 ± 18 | 1.2 ± 0.6 |
| Female sports | | | | | | | | | |
| Basketball | | | | | | | | | |
| EAMC history | 17 | 35 ± 12 | 0.6 ± 0.4 | 17 | 3.8 ± 0.3 | 0.12 ± 0.07 | 11 | 39 ± 21 | 0.8 ± 0.5 |
| Control | 15 | 39 ± 14 | 0.7 ± 0.5 | 15 | 3.9 ± 0.6 | 0.14 ± 0.09 | 11 | 50 ± 23 | 1.0 ± 0.6 |
| Aggregate[a] | 32 | 37 ± 13 | 0.7 ± 0.5 | 32 | 3.9 ± 0.4 | 0.12 ± 0.08 | 22 | 44 ± 22 | 0.9 ± 0.6 |
| Field hockey | | | | | | | | | |
| EAMC history | 12 | 44 ± 10 | 0.5 ± 0.1 | 12 | 3.9 ± 0.4 | 0.07 ± 0.01 | 12 | 49 ± 16 | 0.8 ± 0.3 |
| Control | 6 | 41 ± 11 | 0.4 ± 0.2 | 6 | 3.7 ± 0.2 | 0.07 ± 0.01 | 6 | 42 ± 19 | 0.7 ± 0.4 |
| Aggregate[a] | 18 | 43 ± 10 | 0.5 ± 0.1 | 18 | 3.9 ± 0.3 | 0.07 ± 0.01 | 18 | 47 ± 17 | 0.8 ± 0.3 |
| Gymnastics | | | | | | | | | |
| EAMC history | 4 | 43 ± 6 | 0.3 ± 0.1 | 4 | 3.7 ± 0.2 | 0.04 ± 0.01 | 4 | 45 ± 12 | 0.5 ± 0.1 |
| Control | 3 | 41 ± 3 | 0.3 ± 0.1 | 3 | 3.9 ± 0.1 | 0.05 ± 0.01 | 3 | 37 ± 1 | 0.4 ± 0.1 |
| Aggregate[a] | 7 | 42 ± 5 | 0.3 ± 0.1 | 7 | 3.8 ± 0.2 | 0.05 ± 0.01 | 7 | 42 ± 10 | 0.5 ± 0.1 |
| Soccer | | | | | | | | | |
| EAMC history | 19 | 37 ± 14 | 0.7 ± 0.5 | 19 | 3.7 ± 0.3 | 0.09 ± 0.05 | 10 | 54 ± 19 | 1.5 ± 1.5 |
| Control | 8 | 39 ± 11 | 0.4 ± 0.2 | 8 | 3.9 ± 0.3 | 0.06 ± 0.02 | 7 | 47 ± 15 | 0.8 ± 0.3 |
| Aggregate[a] | 27 | 38 ± 13 | 0.6 ± 0.5 | 27 | 3.7 ± 0.3 | 0.09 ± 0.04 | 17 | 51 ± 18 | 1.2 ± 1.2 |

*(continued)*

**Table 2 (continued)**

| Sport | Sample size for $[Na^+]_{sw}$ (*n*) | $[Na^+]_{sw}$ (mmol/L) | $Na^+_{sw}$ content (g) | Sample size for $[K^+]_{sw}$ (*n*) | $[K^+]_{sw}$ (mmol/L) | $K^+_{sw}$ content (g) | Sample size for $[Cl^-]_{sw}$ (*n*) | $[Cl^-]_{sw}$ (mmol/L) | $Cl^-_{sw}$ content (g) |
|---|---|---|---|---|---|---|---|---|---|
| Softball | | | | | | | | | |
| EAMC history | 14 | 29 ± 8 | 1.2 ± 0.5 | 14 | 3.6 ± 0.5 | 0.25 ± 0.04 | 0 | N/A | N/A |
| Control | 7 | 34 ± 10 | 1.2 ± 0.4 | 7 | 3.9 ± 0.4 | 0.24 ± 0.08 | 0 | N/A | N/A |
| Aggregate[a] | 21 | 31 ± 9 | 1.2 ± 0.4 | 21 | 3.7 ± 0.4 | 0.25 ± 0.05 | 0 | N/A | N/A |
| Tennis | | | | | | | | | |
| EAMC history | 5 | 30 ± 12 | 1.1 ± 0.6 | 5 | 3.4 ± 0.2 | 0.20 ± 0.05 | 5 | 45 ± 24 | 2.5 ± 1.6 |
| Control | 4 | 21 ± 4 | 0.4 ± 0.2 | 4 | 3.3 ± 0.5 | 0.09 ± 0.06 | 4 | 29 ± 6 | 0.7 ± 0.4 |
| Aggregate[a] | 9 | 26 ± 10 | 0.7 ± 0.6 | 9 | 3.4 ± 0.3 | 0.16 ± 0.08 | 9 | 38 ± 19 | 1.7 ± 1.5 |
| Volleyball | | | | | | | | | |
| EAMC history | 8 | 25 ± 3 | 0.6 ± 0.3 | 8 | 3.7 ± 0.3 | 0.18 ± 0.08 | 1 | 19 | 1.1 |
| Control | 4 | 37 ± 8 | 0.8 ± 0.3 | 4 | 3.7 ± 0.2 | 0.13 ± 0.04 | 3 | 27 ± 17 | 1.0 ± 0.7 |
| Aggregate[a] | 12 | 28 ± 8 | 0.7 ± 0.3 | 12 | 3.7 ± 0.3 | 0.16 ± 0.07 | 4 | 25 ± 15 | 1.0 ± 0.6 |
| Aggregates | | | | | | | | | |
| Gender | | | | | | | | | |
| Males | 191 | 45 ± 13[b] | 1.1 ± 0.9[b] | 192 | 5.1 ± 1.3[b] | 0.26 ± 0.28[b] | 192 | 52 ± 20[b] | 2.1 ± 1.9[b] |
| Females | 126 | 36 ± 12 | 0.7 ± 0.5 | 126 | 3.9 ± 0.8 | 0.13 ± 0.09 | 77 | 44 ± 19 | 0.9 ± 0.7 |
| EAMC history | | | | | | | | | |
| EAMC history | 224 | 41 ± 14 | 1.1 ± 0.9 | 224 | 4.6 ± 1.2 | 0.23 ± 0.26 | 188 | 50 ± 20 | 2.0 ± 2.0 |
| Control | 93 | 42 ± 12 | 0.8 ± 0.5 | 94 | 4.6 ± 1.3 | 0.15 ± 0.11 | 81 | 48 ± 19 | 1.2 ± 1.0 |
| Gender, EAMC history | | | | | | | | | |
| Males, EAMC history | 145 | 44 ± 14 | 1.2 ± 1.0 | 145 | 5.0 ± 1.2 | 0.28 ± 0.30 | 145 | 52 ± 21 | 2.3 ± 2.1 |
| Males, control | 46 | 47 ± 11 | 0.9 ± 0.5 | 47 | 5.3 ± 1.5 | 0.17 ± 0.13 | 47 | 52 ± 18 | 1.6 ± 1.1 |
| Females, EAMC history | 79 | 35 ± 12 | 0.7 ± 0.5 | 79 | 3.8 ± 0.4 | 0.14 ± 0.08 | 43 | 46 ± 19 | 0.9 ± 0.8 |
| Females, control | 47 | 37 ± 12 | 0.7 ± 0.5 | 47 | 3.8 ± 0.4 | 0.12 ± 0.09 | 34 | 42 ± 19 | 0.8 ± 0.5 |

*Note*. Data are presented as mean ± *SD*. $Cl^-_{sw}$ = sweat chloride; $[Cl^-]_{sw}$ = sweat chloride concentration; EAMC = exercise-associated muscle cramping; $K^+_{sw}$ = sweat potassium; $[K^+]_{sw}$ = sweat potassium concentration; $Na^+_{sw}$ = sweat sodium; $[Na^+]_{sw}$ = sweat sodium concentration; N/A = not available.
[a]Average for all athletes in each sport. [b]Males different than females ($p < .01$).

**Table 3 Statistically Significant Differences Between Male Sports for All Dependent Variables**

| | American football | Baseball | Basketball | Track and field | Wrestling |
|---|---|---|---|---|---|
| American football | – | $[K^+]$ and KC | $[K^+]$, KC, SR, and $SR_{BSA}$ | $[Cl^-]$, $[K^+]$, $[Na^+]$, and $SR_{BSA}$ | $[K^+]$ and KC |
| Baseball | $[K^+]$ and KC | – | – | $[Cl^-]$ and $[Na^+]$ | – |
| Basketball | $[K^+]$, KC, SR, and $SR_{BSA}$ | – | – | $[Cl^-]$, $[Na^+]$, SR, and $SR_{BSA}$ | – |
| Track and field | $[Cl^-]$, $[K^+]$, $[Na^+]$, and $SR_{BSA}$ | $[Cl^-]$ and $[Na^+]$ | $[Cl^-]$, $[Na^+]$, SR, and $SR_{BSA}$ | – | $[Cl^-]$ and $[Na^+]$ |
| Wrestling | $[K^+]$ and KC | – | – | $[Cl^-]$ and $[Na^+]$ | – |

*Note*. The presence of a dependent variable name at the intersection of two sports indicates statistically significant differences in that variable between those two sports ($p < .01$). $[Cl^-]$ = sweat chloride concentration; $[K^+]$ = sweat potassium concentration; KC = sweat potassium content; $[Na^+]$ = sweat sodium concentration; SR = sweat rate; $SR_{BSA}$ = sweat rate per body surface area.

**Table 4 Statistically Significant Differences Between Female Sports for All Dependent Variables**

| | Basketball | Field hockey | Gymnastics | Soccer | Softball | Tennis | Volleyball |
|---|---|---|---|---|---|---|---|
| Basketball | – | – | – | – | KC and NaC | – | SR and $SR_{BSA}$ |
| Field hockey | – | – | – | – | KC and NaC | $[Na^+]$ | KC and $SR_{BSA}$ |
| Gymnastics | – | – | – | – | KC and NaC | – | KC |
| Soccer | – | – | – | – | KC and NaC | – | KC and $SR_{BSA}$ |
| Softball | KC and NaC | KC and NaC | KC and NaC | KC and NaC | – | KC | KC |
| Tennis | – | $[Na^+]$ | | | KC | – | – |
| Volleyball | SR and $SR_{BSA}$ | KC and $SR_{BSA}$ | KC | KC and $SR_{BSA}$ | KC | – | – |

*Note*. The presence of a dependent variable name at the intersection of two sports indicates statistically significant differences in that variable between those two sports ($p < .01$). KC = sweat potassium content; $[Na^+]$ = sweat sodium concentration; NaC = sweat sodium content; SR = sweat rate; $SR_{BSA}$ = sweat rate per body surface area.

In 17 male tennis players, Bergeron observed cramp-prone athletes had SRs of $2.6 \pm 0.43$ L and $[Na^+]_{sw}$ of $44.5 \pm 3.5$ mmol/L. Later, Stofan et al. (2005) observed five cramp-prone American football players had SRs and $[Na^+]_{sw}$ that ranged between $1.49 \pm 0.60$ to $1.66 \pm 0.27$ L/hr and $52.2 \pm 13.0$ to $56.5 \pm 17.4$ mmol/L, respectively. Comparatively, five noncramping American football players lost $0.99 \pm 0.41$–$1.80 \pm 1.48$ L/hr of sweat and $21.7 \pm 8.7$–$30.4 \pm 13.0$ mmol/L of $Na^+$. Similarly, Horswill et al. (2009) noted six cramp-prone American football players had higher SRs (difference = 0.6 L/hr), $[Na^+]_{sw}$ (difference = 15 mmol/L), and $[K^+]_{sw}$ (difference = 0.5 mmol/L) than eight reference players. Statistically, no author (Horswill et al., 2009; Stofan et al., 2005) demonstrated differences in sweat characteristics between groups, but concluded EAMCs were the result of fluid/electrolyte disturbances. Interestingly, large fluid (upward of 4 L) and electrolyte losses (upward of 10 g of $Na^+$) occurred in these studies (Bergeron, 2003; Horswill et al., 2009; Stofan et al., 2005). Some even showed plasma $[Na^+]$ reductions in the cramp-prone athletes (Horswill et al., 2009). However, not even one EAMC was reported during data collection in any of these field studies (Bergeron, 2003; Horswill et al., 2009; Stofan et al., 2005).

Conversely, our data and that from cohort, observational, and experimental studies do not support this theory. In ~700 male athletes, EAMC was not correlated with $[Na^+]_{sw}$ in American football, soccer, or basketball (Ranchordas et al., 2017). Moreover, body mass loss and serum electrolyte values were similar in endurance athletes who did or did not develop EAMC (Maughan, 1986; Schwellnus et al., 2004; 2011; Sulzer et al., 2005). Acute losses in body fluids (3–5% body mass reduction) and electrolytes (up to 4 g of $Na^+$) did not affect cramp susceptibility when peripheral muscular fatigue was minimized (Braulick et al., 2012; Miller et al., 2010). When dehydrated to −6% of their body mass, resting muscle membrane potential became more negative. Contrary to the dehydration/electrolyte imbalance theory, the membrane became more difficult to depolarize (Costill et al., 1976). The similar serum electrolyte values suggest that both cramp-prone and control athletes had similar osmotic fluid pressures. Consequently, the pressure driving fluid out of the interstitial fluid space would be comparable and be an unlikely explanation for EAMC genesis.

We propose two reasons for the discrepancies in observations (Bergeron, 2003; Horswill et al., 2009; Stofan et al., 2005). First, prior studies had small sample sizes or lacked suitable control groups. When larger sample sizes were collected, few correlations between sweat electrolytes and EAMCs were noted (Ranchordas et al., 2017), though sweat collection method (i.e., stimulated) differed from ours. Small sample sizes are problematic because SRs and sweat electrolyte concentrations vary widely in athletes (Baker, 2017; Baker et al., 2016). $[Na^+]_{sw}$ ranged from <20 to >100 mmol/L in competitive athletes, whereas SRs ranged from <0.5 to >3.0 L/hr (Baker et al., 2016; Ranchordas et al., 2017). Baker et al. (2016) noted average forearm $[Na^+]_{sw}$ of over 300 adult male and female athletes was between $40.8 \pm 16.9$ mmol/L (women) and $48.2 \pm 18.1$ mmol/L (men), whereas SRs ranged from $1.1 \pm 0.57$ (women) to $1.42 \pm 0.72$ L/hr (men). Second, others only examined "severe" EAMCs. Previously (Horswill et al., 2009; Stofan et al., 2005), cramp-prone athletes needed to have previously documented heavy sweat losses, medical records documenting EAMCs, required intravenous fluids, and the EAMC had to disallow exercise. This definition suggests EAMCs were debilitating and biased toward individuals with heavy SRs. However, most EAMCs neither impair athletic performance nor require medical assistance (Hoffman & Fogard, 2011; Schwellnus et al., 2004). EAMCs caused exercise cessation for only 5% of athletes (Hoffman &

**Table 5 Diagnostic and Predictive Results for Sweat Variables**

| Variable | Area under curve [95% CI] | Area under curve, *p* value | Cutoff value | Sensitivity | Specificity | Diagnostic odd ratio [95% CI] |
|---|---|---|---|---|---|---|
| All sports and genders | | | | | | |
| $[Na^+]_{sw}$ | 0.47 [0.40, 0.54] | .19 | 49.24 mmol/L | 0.29 (0.23–0.35) | 0.76 (0.67–0.84) | 1.29 [0.74, 2.26] |
| $Na^+_{sw}$ content | 0.61 [0.54, 0.67] | .001[a] | 1.15 g | 0.31 (0.25–0.38) | 0.87 (0.79–0.92) | 3.06 [1.57, 5.98] |
| $[K^+]_{sw}$ | 0.52 [0.44, 0.58] | .33 | 4.25 mmol/L | 0.52 (0.46–0.59) | 0.59 (0.48–0.68) | 1.54 [0.95, 2.51] |
| $K^+_{sw}$ content | 0.61 [0.54, 0.67] | .001[a] | 0.2 g | 0.34 (0.28–0.40) | 0.83 (0.74–0.89) | 2.47 [1.33, 4.51] |
| $[Cl^-]_{sw}$ | 0.53 [0.45, 0.60] | .26 | 38.0 mmol/L | 0.72 (0.65–0.78) | 0.32 (0.23–0.43) | 1.20 [0.69, 2.12] |
| $Cl^-_{sw}$ content | 0.62 [0.55, 0.69] | .0004[a] | 2.33 g | 0.28 (0.22–0.35) | 0.95 (0.88–0.98) | 7.41 [2.58, 21.29] |
| SR | 0.57 [0.49, 0.63] | .02 | 1.02 L/hr | 0.50 (0.44–0.56) | 0.60 (0.50–0.69) | 1.51 [0.95, 2.41] |
| SR/BSA | 0.55 [0.48, 0.61] | .07 | 0.54 $L{\cdot}hr^{-1}{\cdot}m^{-2}$ | 0.49 (0.43–0.56) | 0.61 (0.51–0.69) | 1.52 [0.96, 2.43] |
| All sports and genders excluding American football | | | | | | |
| $[Na^+]_{sw}$ | 0.46 [0.38, 0.54] | .19 | 50.95 mmol/L | 0.21 (0.15–0.28) | 0.84 (0.74–0.91) | 1.39 [0.66, 2.97] |
| $Na^+_{sw}$ content | 0.55 [0.46, 0.63] | .11 | 0.47 g | 0.77 (0.69–0.83) | 0.37 (0.27–0.49) | 1.99 [1.07, 3.7] |
| $[K^+]_{sw}$ | 0.48 [0.40, 0.56] | .35 | 4.36 mmol/L | 0.29 (0.22–0.36) | 0.84 (0.74–0.91) | 2.16 [1.03, 4.49] |
| $K^+_{sw}$ content | 0.57 [0.48, 0.65] | .051 | 0.10 g | 0.66 (0.57–0.73) | 0.49 (0.37–0.60) | 1.79 [1.00, 3.21] |
| $[Cl^-]_{sw}$ | 0.52 [0.42, 0.60] | .35 | 37.5 mmol/L | 0.70 (0.61–0.78) | 0.37 (0.26–0.49) | 1.37 [0.70, 2.69] |
| $Cl^-_{sw}$ content | 0.56 [0.46, 0.65] | .09 | 0.61 g | 0.82 (0.74–0.88) | 0.35 (0.24–0.48) | 2.51 [1.21, 5.20] |
| SR | 0.52 [0.43, 0.60] | .29 | 0.63 L/hr | 0.82 (0.75–0.87) | 0.27 (0.18–0.39) | 1.71 [0.87, 3.35] |
| SR/BSA | 0.50 [0.42, 0.58] | .48 | 0.69 $L{\cdot}hr^{-1}{\cdot}m^{-2}$ | 0.21 (0.15–0.28) | 0.86 (0.76–0.92) | 1.57 [0.72, 3.41] |
| Female sports | | | | | | |
| $[Na^+]_{sw}$ | 0.44 [0.33, 0.53] | .11 | 50.95 mmol/L | 0.14 (0.08–0.23) | 0.91 (0.80–0.97) | 1.74 [0.52, 5.81] |
| $Na^+_{sw}$ Content | 0.57 [0.45, 0.67] | .11 | 0.5 g | 0.66 (0.55–0.76) | 0.53 (0.39–0.67) | 2.23 [1.05, 4.71] |
| $[K^+]_{sw}$ | 0.43 [0.32, 0.53] | .09 | 3.29 mmol/L | 0.95 (0.88–0.98) | 0.11 (0.05–0.23) | 2.23 [0.57, 8.77] |
| $K^+_{sw}$ Content | 0.57 [0.46, 0.67] | .08 | 0.21 g | 0.31 (0.21–0.42) | 0.85 (0.72–0.93) | 2.53 [0.99, 6.48] |
| $[Cl^-]_{sw}$ | 0.55 [0.41, 0.67] | .23 | 38.8 mmol/L | 0.63 (0.48–0.76) | 0.53 (0.37–0.69) | 1.89 [0.76, 4.74] |
| $Cl^-_{sw}$ Content | 0.57 [0.42, 0.68] | .16 | 0.65 g | 0.65 (0.50–0.78) | 0.33 (0.18–0.53) | 0.93 [0.33, 2.68] |
| SR | 0.52 [0.42, 0.61] | .33 | 0.64 L/hr | 0.73 (0.63–0.81) | 0.35 (0.24–0.49) | 1.46 [0.71, 2.99] |
| SR/BSA | 0.51 [0.41, 0.61] | .39 | 0.44 $L{\cdot}hr^{-1}{\cdot}m^{-2}$ | 0.51 (0.41–0.61) | 0.50 (0.37–0.63) | 1.04 [0.53, 2.05] |
| Male sports | | | | | | |
| $[Na^+]_{sw}$ | 0.44 [0.35, 0.52] | .09 | 64.92 mmol/L | 0.09 (0.05–0.15) | 0.98 (0.89–0.99) | 4.43 [0.56, 34.84] |
| $Na^+_{sw}$ Content | 0.60 [0.51, 0.68] | .009[a] | 1.14 g | 0.39 (0.32–0.48) | 0.89 (0.77–0.95) | 5.37 [2.00, 14.41] |
| $[K^+]_{sw}$ | 0.46 [0.36, 0.55] | .22 | 4.36 mmol/L | 0.72 (0.65–0.79) | 0.29 (0.19–0.44) | 1.11 [0.54, 2.29] |
| $K^+_{sw}$ Content | 0.59 [0.49, 0.67] | .02 | 0.23 g | 0.28 (0.22–0.36) | 0.91 (0.79–0.97) | 4.18 [1.41, 12.40] |
| $[Cl^-]_{sw}$ | 0.48 [0.38, 0.57] | .32 | 81.0 mmol/L | 0.12 (0.07–0.18) | 0.96 (0.86–0.99) | 2.99 [0.66, 13.45] |
| $Cl^-_{sw}$ Content | 0.60 [0.50, 0.67] | .015 | 2.3 g | 0.36 (0.29–0.44) | 0.91 (0.80–0.97) | 6.08 [2.06, 17.88] |
| SR | 0.55 [0.46, 0.63] | .12 | 1.8 L/hr | 0.25 (0.19–0.32) | 0.88 (0.77–0.94) | 2.48 [0.98, 6.27] |
| SR/BSA | 0.53 [0.44, 0.62] | .23 | 0.68 $L{\cdot}hr^{-1}{\cdot}m^{-2}$ | 0.36 (0.29–0.44) | 0.78 (0.65–0.88) | 2.04 [0.97, 4.29] |
| Male sports excluding American football | | | | | | |
| $[Na^+]_{sw}$ | 0.44 [0.31, 0.56] | .19 | 49.24 mmol/L | 0.35 (0.25–0.47) | 0.69 (0.49–0.84) | 1.24 [0.45, 3.42] |
| $Na^+_{sw}$ Content | 0.47 [0.33, 0.59] | .32 | 1.14 g | 0.20 (0.12–0.31) | 0.91 (0.73–0.98) | 2.63 [0.55, 12.54] |
| $[K^+]_{sw}$ | 0.47 [0.33, 0.59] | .33 | 4.36 mmol/L | 0.54 (0.42–0.65) | 0.57 (0.37–0.74) | 1.49 [0.58, 3.86] |
| $K^+_{sw}$ Content | 0.51 [0.36, 0.63] | .45 | 0.14 g | 0.41 (0.31–0.53) | 0.69 (0.49–0.84) | 1.62 [0.59, 4.42] |
| $[Cl^-]_{sw}$ | 0.44 [0.30, 0.57] | .20 | 84.0 mmol/L | 0.09 (0.05–0.19) | 0.96 (0.79–0.99) | 2.41 [0.28, 20.67] |
| $Cl^-_{sw}$ Content | 0.46 [0.31, 0.59] | .29 | 2.41 g | 0.14 (0.08–0.24) | 0.96 (0.79–0.99) | 3.67 [0.44, 30.33] |
| SR | 0.44 [0.29, 0.56] | .17 | 2.48 L/hr | 0.07 (0.03–0.16) | 0.96 (0.79–0.99) | 1.69 [0.19, 15.29] |
| SR/BSA | 0.43 [0.29, 0.56] | .18 | 1.22 $L{\cdot}hr^{-1}{\cdot}m^{-2}$ | 0.07 (0.03–0.16) | 0.96 (0.79–0.99) | 1.69 [0.19, 15.29] |

*(continued)*

**Table 5 *(continued)***

| Variable | Area under curve [95% CI] | Area under curve, *p* value | Cutoff value | Sensitivity | Specificity | Diagnostic odd ratio [95% CI] |
|---|---|---|---|---|---|---|
| American football | | | | | | |
| $[Na^+]_{sw}$ | 0.43 [0.29, 0.55] | .16 | 50.24 mmol/L | 0.38 (0.28–0.49) | 0.65 (0.45–0.81) | 1.14 [0.43, 3.04] |
| $Na^+_{sw}$ content | 0.72 [0.59, 0.81] | .0001[a] | 1.18 g | 0.58 (0.47–0.69) | 0.87 (0.68–0.95) | 9.25 [2.5, 33.88] |
| $[K^+]_{sw}$ | 0.42 [0.28, 0.55] | .14 | 4.57 mmol/L | 0.79 (0.69–0.87) | 0.21 (0.09–0.40) | 1.04 [0.33, 3.23] |
| $K^+_{sw}$ content | 0.68 [0.55, 0.78] | .001[a] | 0.19 g | 0.61 (0.49–0.71) | 0.74 (0.54–0.87) | 4.39 [1.55, 12.45] |
| $[Cl^-]_{sw}$ | 0.51 [0.37, 0.63] | .43 | 27.2 mmol/L | 0.97 (0.91–0.99) | 0.13 (0.04–0.31) | 5.14 [0.81, 32.84] |
| $Cl^-_{sw}$ content | 0.71 [0.58, 0.81] | .0001[a] | 2.3 g | 0.57 (0.45–0.67) | 0.88 (0.69–0.97) | 9.19 [2.52, 33.52] |
| SR | 0.65 [0.52, 0.75] | .005[a] | 1.44 L/hr | 0.54 (0.44–0.65) | 0.70 (0.52–0.84) | 2.81 [1.11, 7.14] |
| SR/BSA | 0.62 [0.49, 0.73] | .02 | $0.75\ L{\cdot}hr^{-1}{\cdot}m^{-2}$ | 0.34 (0.24–0.44) | 0.93 (0.77–0.98) | 6.36 [1.41, 28.82] |

*Note*. BSA = body surface area; $Cl^-_{sw}$ = sweat chloride; CI = confidence interval; g = grams; $K^+_{sw}$ = sweat potassium; $Na^+_{sw}$ = sweat sodium; $[Na^+]_{sw}$ = sweat sodium concentration; $[K^+]_{sw}$ = sweat potassium concentration; $[Cl^-]_{sw}$ = sweat chloride concentration; SR = sweat rate.
[a]Significant area under the curve indicating a useful test for identifying exercise-associated muscle cramping-prone athletes ($p < .01$).

Fogard, 2011). Our definition of EAMC history was broader and allowed for a larger range of EAMC severity.

Our second main observation was our receiver operator characteristic analysis which indicated that sweat characteristics were not predictive of EAMCs in every sport except American football. Gross SR, $Na^+_{sw}$ content, $K^+_{sw}$ content, and $Cl^-_{sw}$ content significantly predicted EAMCs in American football players. When sweat electrolyte concentration data were paired with SRs, we noted relevant odds ratios for all sweat electrolytes. When normalized using BSA, American football players with an SR/BSA >$0.75\ L{\cdot}hr^{-1}{\cdot}m^{-2}$ had approximately six times greater odds of being cramp-prone than players with an SR/BSA <$0.75\ L{\cdot}hr^{-1}{\cdot}m^{-2}$. We propose two reasons why this was only significant in American football players. First, our sample size was highest in American football. Second, American football is unique in that players compete at high intensities during the hottest part of the year (in the Northern hemisphere), they are often much larger than other athletes, and they wear protective equipment which affects sweat losses (Davis et al., 2016). Thus, given the multifactorial nature of EAMCs (Miller, 2020), American football players may experience more intrinsic or extrinsic EAMC risk factors, which can coalesce with sweat losses to induce EAMCs.

This suggests some athletes with high SRs may have an increased EAMC risk. However, to better identify cramp-prone American football athletes, sweat electrolyte concentration, and SR are required. Notably, gross SR is a clinically friendly measure, easy to perform in the field, and useful for identifying heavy sweaters in American football. Nutritionally, clinicians should quantify individual SR and educate athletes on their personal needs (McDermott et al., 2017). When education is included as an intervention for hydration maintenance, athletes improved hydration and athletic performance (Cleary et al., 2012). Therefore, our results suggest that some American football players with high SRs may benefit from similar interventions for EAMC prevention, as they experience a higher incidence of EAMCs than other sports (Cooper et al., 2006; Tripp et al., 2015; Yeargin et al., 2016).

Our final observation was the differences in sweat characteristics between genders and sports. We observed males had 15%, 20%, 24%, and 39% higher $[Cl^-]_{sw}$, $[Na^+]_{sw}$, $[K^+]_{sw}$, and SR, respectively. Even when normalized using BSA, gender differences remained. Males have higher SRs (Baker et al., 2018) and sweat electrolyte concentrations than females, which is consistent with some previous reports (Lara et al., 2016) but not all (Amano et al., 2017). Sweat electrolyte concentration differences may be due to SR differences, as ion absorption rates appear similar between genders (Amano et al., 2017). We recommend clinicians consider gender and sport when determining fluid and electrolyte replacement needs, as recent recommendations are to individualize hydration and nutrition replacement (McDermott et al., 2017).

We acknowledge our study's limitations. First, our field design disallowed control over variables that may affect sweat characteristics (e.g., preexercise hydration status, ingested fluid type and electrolyte content, exercise duration). As dehydration can cause elevated $[Na^+]_{sw}$ and $[Cl^-]_{sw}$ compared with euhydrated conditions (Morgan et al., 2004), our sweat electrolyte concentrations may be higher than normal. Second, our athletes' self-reported cramp history and we did not distinguish between local and "whole-body" EAMCs. Third, we applied sweat patches before exercise and sweating. Consequently, our sweat samples included primary sweat, which may lead to elevated electrolyte concentrations. Fourth, none of our athletes experienced EAMCs during data collection and some athletes were tested outside of their normal sporting conditions. For example, ~71% ($n = 79$) of our American football data were collected during off-season conditioning activities when protective equipment and contact were limited. As these variables can affect blood electrolyte levels and SRs (Davis et al., 2016; Fowkes-Godek & Bartolozzi, 2009), our data may be underrepresenting some sweat losses in American football. Finally, Type II errors may be present in some of our statistical analyses (e.g., $Na^+_{sw}$ content).

## Novelty

This is the first study to evaluate sweat variables in a large sample of male and female competitive athletes with and without a history of EAMCs in numerous sports during habitual training. We observed minimal differences in sweat characteristics between cramp-prone athletes and control athletes. Moreover, we noted limited clinical relevance and predictability of EAMCs for most sweat characteristics in the majority of sports tested.

## Practical Application

First, some American football players with high SRs may benefit from electrolyte supplementation and/or hydration monitoring. For most athletes, overstressing the necessity of fluids or electrolytes to prevent EAMCs is unnecessary. Overconsumption of fluids to prevent EAMCs can result in life-threatening disorders like hyponatremia (Hew-Butler et al., 2015; Stevens, 2014). As most research suggests cramping is due to neurological alterations rather than fluid and electrolyte losses (Braulick et al., 2012; Schwellnus et al., 2004; 2009; 2011), clinicians may more successfully prevent EAMCs by mitigating fatigue or nervous system excitability. Second, clinicians should individualize fluid and electrolyte replacement, as significant variability in sweat losses exist between genders and sports. One-size-fits-all recommendations should be avoided to prevent over or under hydration (McDermott et al., 2017).

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