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Gastric Emptying After Pickle-Juice Ingestion in Rested, Euhydrated Humans

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Context: Small volumes of pickle juice (PJ) relieve muscle cramps within 85 seconds of ingestion without significantly affecting plasma variables. This effect may be neurologic rather than metabolic. Understanding PJ's gastric emptying would help to strengthen this theory.

Objective: To compare gastric emptying and plasma variables after PJ and deionized water (DIW) ingestion.

Design: Crossover study.

Setting: Laboratory.

Patients or Other Participants: Ten men (age = 25.4 ± 0.7 years, height = 177.1 ± 1.6 cm, mass = 78.1 ± 3.6 kg).

Intervention(s): Rested, euhydrated, and eunatremic participants ingested 7 mL·kg^{-1} body mass of PJ or DIW on separate days.

Main Outcome Measure(s): Gastric volume was measured at 0, 5, 10, 20, and 30 minutes postingestion (using the phenol red dilution technique). Percentage changes in plasma volume and plasma sodium concentration were measured preingestion (−45 minutes) and at 5, 10, 20, and 30 minutes postingestion.

Results: Initial gastric volume was 624.5 ± 27.4 mL for PJ and 659.5 ± 43.8 mL for DIW ($P > .05$). Both fluids began to empty within the first 5 minutes (volume emptied: PJ = 219.2 ± 39.1 mL, DIW = 305.0 ± 40.5 mL, $P < .05$). Participants who ingested PJ did not empty further after the first 5 minutes ($P > .05$), whereas in those who ingested DIW, gastric volume decreased to 111.6 ± 39.9 mL by 30 minutes ($P < .05$). The DIW group emptied faster than the PJ group between 20 and 30 minutes postingestion ($P < .05$). Within 5 minutes of PJ ingestion, plasma volume decreased 4.8% ± 1.6%, whereas plasma sodium concentration increased 1.6 ± 0.5 mmol·L^{-1} ($P < .05$). Similar changes occurred after DIW ingestion. Calculated plasma sodium content was unchanged for both fluids ($P > .05$).

Conclusions: The initial decrease in gastric volume with both fluids is likely attributable to gastric distension. Failure of the PJ group to empty afterward is likely due to PJ's osmolality and acidity. Cardiovascular reflexes resulting from gastric distension are likely responsible for the plasma volume shift and rise in plasma sodium concentration despite nonsignificant changes in plasma sodium content. These data support our theory that PJ does not relieve cramps via a metabolic mechanism.

Key Words: acetic acid, electrolytes, sodium, stomach, vinegar

Key Points

- Ingestion of large volumes of pickle juice and deionized water resulted in initially similar gastric-emptying rates.
- However, compared with ingestion of deionized water, gastric volume was greater at 20 and 30 minutes after ingestion of pickle juice. This difference is likely due to the osmolality and acidity of pickle juice.
- After ingestion of pickle juice, gastric distension likely triggers cardiovascular reflexes, causing hypotonic fluid to shift out of the intravascular space.

Skeletal muscle cramps occurring during or shortly after exercise have been termed *exercise-associated muscle cramps* (EAMC). These cramps affect athletes including marathoners[1] and American football players.[2] Despite their prevalence, the cause of EAMC is unknown. The unclear cause has resulted in health care professionals using a variety of strategies to treat and prevent EAMC, often with little perceived success.[3] Moreover, many of these treatments and prevention strategies are based on little or no scientific evidence.

One treatment for EAMC with little scientific support is ingesting pickle juice (PJ), a salty, acidic brine used to pickle cucumbers. In one study,[4] approximately 25% (92 of 370) of certified athletic trainers provided PJ to athletes experiencing acute EAMC; most provided only a few ounces (≤100 mL). It is interesting that some health care professionals claim that ingesting these volumes of PJ can relieve acute EAMC within 35 seconds of ingestion.[5] Until recently, these claims had been purely anecdotal. In a recent double-blind study,[6] we observed that small volumes (74 mL) of PJ relieved electrically induced muscle cramps faster than water or no fluid at all (85, 134, and 153 seconds, respectively). Although many health care professionals credit the high electrolyte content in PJ for the rapid cessation of EAMC,[4] we have shown that ingesting these volumes of PJ did not change plasma variables (eg, plasma osmolality, electrolytes, or plasma volume [PV]) in euhydrated[7] or hypohydrated (3% body-mass reduction) humans.[6] Based on these observations, we[6] theorized that the rapid cessation of cramping after PJ ingestion indicated a neurologic rather than a metabolic effect.

Understanding how quickly PJ leaves the stomach would signify how quickly the nutrients and fluid in PJ could be absorbed and circulated to a cramping muscle. Other authors[8] have shown that fluids with high osmolality and low pH impair gastric emptying. Moreover, acetic acid, a primary ingredient in PJ, slows gastric emptying of starchy meals.[9] Currently, no data on the gastric emptying of PJ exist. If gastric emptying of PJ is slow, as hypothesized, the nutrients and fluid in PJ would not be absorbed or circulated quickly enough to relieve acute EAMC. This would help to strengthen our theory that PJ does not alleviate skeletal muscle cramps via a metabolic mechanism.

Therefore, we asked the following questions: (1) How does the gastric emptying of PJ compare with that of deionized water (DIW)? (2) How much PJ empties from the stomach within the first 5 minutes of ingestion? (3) How do plasma sodium concentration ($[Na]_p$) and PV change after ingestion of large boluses of PJ and DIW? Due to the high osmolality and low pH of PJ, we also questioned how palatable participants would find it and if this would lead to feelings of nausea over the course of testing. We hypothesized that PJ would have a slower emptying time than DIW, that little PJ would empty from the stomach within the first 5 minutes of ingestion, that $[Na]_p$ and PV would increase after PJ ingestion, and that DIW would be more palatable and cause less nausea than PJ.

METHODS

Experimental Design

The research involved a crossover, 2 × 5 factorial design with repeated measures on time-guided data collection. The independent variables were drink (PJ [strained from sliced dill pickles; Vlasic Pickles, Pinnacle Foods Group LLC, Cherry Hill, NJ] and DIW) and time (0, 5, 10, 20, and 30 minutes postingestion). For blood data, our independent variables and factor levels were the same, except that the baseline blood sample was drawn at time −45 minutes rather than at 0 minutes. Our dependent variables were phenol red concentration, hematocrit, hemoglobin concentration, $[Na^+]_p$, nausea, and palatability. Plasma osmolality was measured to characterize hydration status before fluid ingestion.

Gastric-Volume, Gastric-Secretion, and Gastric Emptying-Rate Equations

Phenol red concentrations were used to calculate gastric volumes and gastric secretions. Using phenol red to determine gastric volume is a reliable technique[10] commonly used in vivo gastric-emptying experiments.[10–13] Initial gastric volume (IGV) and subsequent gastric volume (SGV) are calculated with Equations 1 and 2, respectively. Gastric-emptying rate (GER) and gastric-secretion volume (GSV) are calculated with Equations 3 and 4, respectively.

$$\mathrm{IGV} = \mathrm{TBV} \times \left(\frac{\mathrm{TBC}}{\mathrm{GS_{pre}}}\right) \quad (1)$$

$$\mathrm{SGV} = \frac{\left[\mathrm{STV} \times \left(\mathrm{STC} - \mathrm{GS_{pre}}\right)\right]}{\left(\mathrm{GS_{post}} - \mathrm{GS_{pre}}\right)} \quad (2)$$

$$\mathrm{GER} = \frac{(\mathrm{GV_1} - \mathrm{GV_2})}{(\text{time between samples})} \quad (3)$$

$$\mathrm{GSV} = \mathrm{GV} \times \left[1 - \left(\frac{\mathrm{GC_{pre}}}{\mathrm{GC_{post}}}\right)\right] \quad (4)$$

where TBV is the total beverage volume ingested (7 mL fluid per kilogram body mass); TBC is the test beverage concentration of phenol red (approximately 25 ppm); GS_{pre} is the gastric sample's concentration of phenol red before the phenol red stock solution is added and mixed; STV is the volume of phenol red stock infused (approximately 10 mL); STC is the phenol red concentration of the stock solution (approximately 500 ppm); GS_{post} is the gastric sample's concentration of phenol red after the addition and mixing of the phenol red stock solution; GV_1 and GV_2 are the first and second gastric volumes, respectively, used in the determination of GER; GV is the gastric volume for a particular time point at which secretion volume is calculated; GC_{pre} is the phenol red concentration of the initial gastric sample from a subsequent sample; and GC_{post} is the phenol red concentration of the gastric sample after mixing with the phenol red stock solution from the previous sample. For example, to determine GSV at 10 to 20 minutes, the first gastric-sample concentration of phenol red at time 30 minutes (before phenol red stock addition) constituted the GC_{pre} and the second gastric-sample concentration of phenol red at time 20 minutes (post minus pre phenol red stock addition) constituted the GC_{post}.

Participants

Ten healthy men (age = 25.4 ± 0.7 years, height = 177.1 ± 1.6 cm, mass = 78.1 ± 3.6 kg) completed the study and were compensated for their time. Volunteers were excluded from participating if they (1) were women, (2) had gastrointestinal problems, (3) had experienced any upper extremity injury or surgery within the previous 6 months, or (4) self-reported any neurologic, cardiovascular, or bloodborne diseases. (Participants with a history of upper extremity injury or surgery were excluded to avoid potential problems with blood procurement due to scar tissue.) All procedures were approved by our university's institutional review board, and participants provided written informed consent.

Testing Procedures

Participants were instructed to refrain from strenuous exercise during the 24 hours before the study began, to eat a light meal (eg, pasta or a sandwich), and to then fast for 12 hours immediately before reporting to the laboratory. They were allowed to drink fluids ad libitum before the 12-hour fast but were instructed to drink only water (ad libitum) during the 12 hours immediately preceding experimentation to facilitate gastric emptying of the meal.

Participants reported to the exercise physiology laboratory on 2 days separated by at least 72 hours. They voided their bladders, were weighed, and reported their degree of nausea (100-mm visual analog scale: 0 = *no nausea*, 100 = *extreme nausea*). Participants were seated in a semirecum-

bent position and given 5 minutes to ingest 5 mL·kg^{-1} body mass of tap water for hydration before testing. They remained seated for 30 minutes, during which a sterile, single-use 20-gauge venous catheter (Becton Dickinson, Sandy, UT) was inserted into a superficial arm vein. The catheter was attached to a 3-way stopcock (Kendall Argyle, Mansfield, MA) via a small extension tube. At the end of 30 minutes, a 5-mL blood sample was drawn to serve as the baseline blood sample (−45 minutes). Participants then voided their bladders completely, were weighed, and returned to a seated position, where they remained for the duration of the experiment.

While seated, the distance of each participant's upper gastrointestinal tract was estimated by measuring the distance from the tip of the nose, around the ear, to the participant's xiphoid process. This distance was marked on a nasogastric tube (12 French gauge Levin, Bard Medical Division, Covington, GA) with a sterile marker. Both the nasal passage and nasogastric tube were coated with lidocaine hydrochloride (2%) jelly (Akorn, Inc, Buffalo Grove, IL) to minimize discomfort to the nasal passage and upper gastrointestinal tract. A topical anesthetic spray (HurriCaine, Beutlich Pharmaceuticals LP, Waukegan, IL) was sprayed on the back of the throat to dull the gag reflex and facilitate nasogastric-tube placement. Participants then inserted the nasogastric tube through the nasal passage to the marked position on the tube. The end of the nasogastric tube was connected to a 3-way stopcock. The second port of the stopcock was used to collect gastric samples and infuse solutions; the third port was connected to a 60-mL syringe to facilitate mixing of the stomach contents.

The location of the nasogastric tube was confirmed by using a 60-mL syringe to infuse 60 mL of DIW and then immediately aspirating the fluid. If all 60 mL of infused fluid was aspirated, the tube was marked at that location for future reference. If less than 60 mL was aspirated, the tube was repositioned and aspiration was attempted again. Only when all 60 mL of infused fluid was aspirated was the tube secured to the participant with a suction-tube attachment device (Hollister Inc, Libertyville, IL). The stomach was rinsed 3 times with DIW until the aspirate remained clear. The measuring and placement of the nasogastric tube required approximately 15 minutes to complete. After nasogastric-tube placement, participants rested for 30 minutes to ensure emptying of any residual fluid that had not been aspirated.

The GV was determined by the double-sampling technique described by George[11] and modified by Beckers et al.[10] Participants were given 90 seconds to drink a single bolus (7 mL·kg^{-1} body mass) of chilled (3°C) PJ or DIW. Descriptive statistics of each drink's composition are found in the Table. These drinks were premixed with approximately 25 ppm phenol red (Sigma-Aldrich Corporation, St Louis, MO), a poorly absorbed indicator dye,[12] and chilled to facilitate quick ingestion. Using a large bolus of fluid is often a delimitation in gastric-emptying research.[14–17] We are unaware of any gastric-emptying researchers who have attempted to validate or ascertain the gastric emptying of a single, small bolus of fluid (eg, <150 mL). Whether a smaller bolus would provide valid gastric emptying information was unknown, so we provided a standard volume of fluid (7 mL·kg^{-1} body weight) that is used in gastric-emptying research. Therefore, our participants ingested a larger volume of PJ than is typically given to athletes experiencing EAMC.[4] The containers holding the treatment drinks were weighed before and after ingestion to determine how much of the fluid was actually ingested.

Table. Pickle Juice and Deionized Water Composition (Mean ± SE)

	Pickle Juice[a]	Deionized Water
Osmolality (mOsmol·kg H_20^{-1})	1325 ± 1	1 ± 0
pH	3.2 ± 0.0	6.8 ± 0.1
Specific gravity	1.022 ± 0	1.0 ± 0
Sodium concentration (mmol·L^{-1})	934.5 ± 1.5	0.4 ± 0.3
Potassium concentration (mmol·L^{-1})	12.0 ± 1.0	Not detectable
Magnesium concentration (mmol·L^{-1})	10.4 ± 1.2	Not detectable
Calcium concentration (mmol·L^{-1})	21.35 ± 0.25	0.23 ± 0.01

[a] Pickle juice was different from deionized water for all dependent variables ($P < .05$). Fluid composition was determined in duplicate.

After ingestion, participants' stomach contents were mixed via repeated aspiration and infusion for 1 minute with a 60-mL syringe. Approximately 20 mL of the stomach contents were drawn into the 60-mL syringe to remove any dead space from the nasogastric tube. A 5-mL gastric sample was then collected (time 0), and participants reported the palatability of the ingested fluid (100-mm visual analog scale: 0 = *extremely unpalatable*, 100 = *extremely palatable*).

Two minutes before subsequent sampling times, the stomach contents were mixed for 1 minute, the dead space was removed, and a 5-mL gastric sample was collected. Ten mL of a 500-ppm phenol red stock solution was then infused via the nasogastric tube and mixed with the stomach contents for 1 minute. Another 5-mL gastric sample was then collected. Participants reported their nausea, and a 5-mL blood sample was collected. The catheter and nasogastric-tube assembly was removed after the last gastric sample was taken, and participants were excused.

All syringes used to infuse fluid were weighed before and after infusion to determine how much fluid was actually infused. The same procedures were performed on the second testing session at approximately the same time of day. The only difference between testing sessions was the treatment fluid ingested. Fluid order was randomized and counterbalanced using a Latin square before testing.

Gastric-Sample Analyses

Gastric samples were filtered with nonsterile, hydrophilic 0.45-μm filters (Sartorius AG, Goettingen, Germany). The gastric sample (0.5 mL) was added to 4.5 mL of a sodium phosphate bicarbonate dodecahydrate buffer solution. This solution was mixed and analyzed for phenol red concentration in duplicate with a spectrophotometer (Victor 3; PerkinElmer, Shelton, CT) with the absorbance read at 560 nm.

Blood Analysis Procedures

Blood for hematocrit analysis was drawn into heparinized microcapillary tubes and centrifuged for 5 minutes at 3000 rpm (model Micro-MB; International Equipment Company, Needham Heights, MA) and read using a

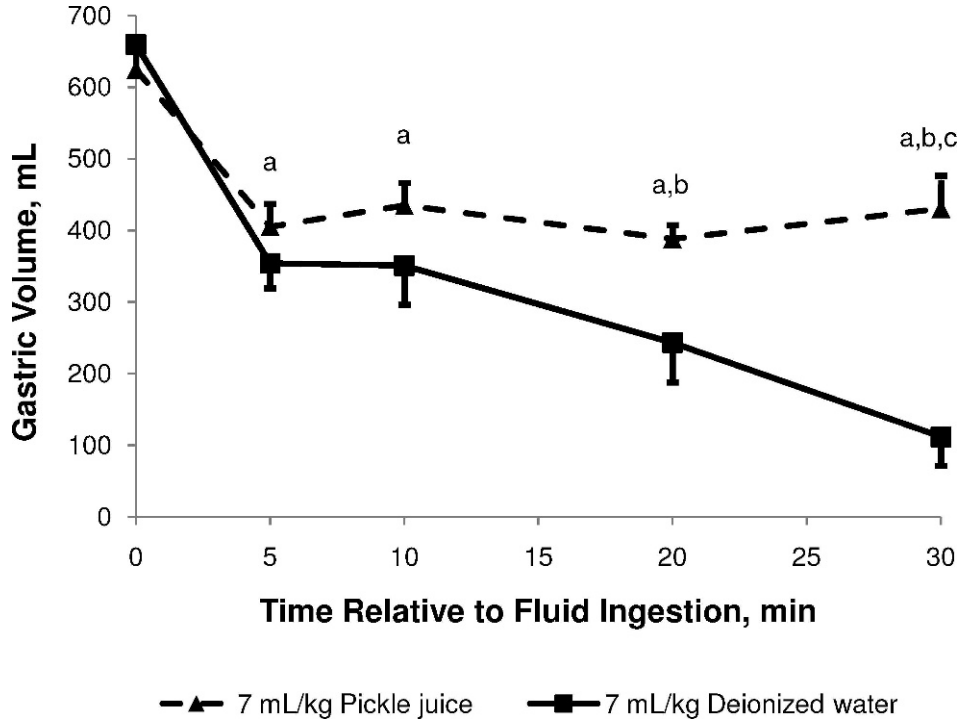

Figure 1. Gastric volumes (mean ± SE) after ingestion of 7 mL·kg^{-1} body mass of pickle juice and deionized water (n = 10). [a] Indicates gastric volume after ingestion of either pickle juice or deionized water was less than at 0 minutes. [b] Indicates that gastric volume after ingestion of pickle juice was greater than after ingestion of deionized water. [c] Indicates that gastric volume after ingestion of deionized water was less at 30 minutes than at 5 minutes. The α level was set at <.05.

microcapillary reader (model IEC 2201; Damon/IEC, Needham Heights, MA). Hemoglobin concentration was measured by mixing 20 μL of whole blood with 5 mL of cyanomethemoglobin reagent and reading the absorbance at 540 nm on a spectrophotometer. Hematocrit and hemoglobin were measured in triplicate immediately after sampling and averaged for each blood sample for statistical analyses and calculations. Hematocrit and hemoglobin were used to calculate changes in PV per the Dill and Costill equation.[18] Hematocrit, hemoglobin, and $[Na^+]_p$ were used to calculate the percentage change in plasma sodium content according to the Greenleaf et al equation.[19]

After the last blood sample was collected, all blood samples were centrifuged at 3000 rpm for 15 minutes at 3°C (centrifuge model 5403; Eppendorf North America, Inc, New York, NY). Plasma was removed from the packed red blood cells and plasma electrolytes were analyzed using an ion-selective electrode system (model 8 electrolyte analyzer; Nova Biomedical, Waltham, MA). Plasma osmolality and $[Na^+]_p$ were measured in duplicate and averaged for statistical analyses. Plasma osmolality was determined via freezing-point depression osmometry (model 3D3; Advanced Instruments, Inc, Norwood, MA) and used as the primary indicator of hydration. A plasma osmolality of 290 mOsm·kg H_2O^{-1} or less indicated euhydration.[20]

Statistical Analyses

Differences in GV, GER, GSV, $[Na^+]_p$, percentage change in $[Na]_p$, nausea, and percentage change in PV over time between PJ and DIW were determined with separate 2-way, repeated-measures analyses of variance for drink and time. Tukey-Kramer post hoc tests were used when F values were significant. Dependent t tests were used to determine differences in plasma osmolality before fluid ingestion and palatability differences between PJ and DIW. All statistical analyses were performed with Number Cruncher Statistical Software (version 2007; Kaysville, UT). Significance was set at $P < .05$.

RESULTS

Data are presented as mean ± SE. Participants were similarly hydrated before fluid ingestion each day (PJ = 284 ± 1 mosm·kg H_2O^{-1}, DIW = 285 ± 1 mosm·kg H_2O^{-1}, $t_9 = 0.2$, $P = .86$).

GV, GER, and GSV

Participants ingested 546.6 ± 24.9 mL of PJ and 546.4 ± 26.1 mL of DIW ($t_9 = 0.2$, $P = .89$). Based on the volume and sodium content of each drink, participants ingested 510.8 mmol (12 g) of sodium with PJ and 0.2 mmol (5 mg) of sodium with DIW.

The GV differed over time between drinks ($F_{5,45} = 10.5$, $P < .001$; Figure 1). Initial GV did not differ between fluids ($P > .05$). Both PJ and DIW emptied within the first 5 minutes postingestion (volume emptied: PJ = 219.2 ± 39.1 mL, DIW = 305.0 ± 40.5 mL; $P < .05$). Subsequently, however, PJ did not empty further for the duration of the experiment ($P > .05$). In contrast, DIW continued to empty over the course of experimentation; GV was lower at 30 minutes than at baseline and at 5 minutes ($P < .05$). Moreover, GVs after DIW ingestion were lower than after PJ ingestion at 20 and 30 minutes ($P < .05$).

The GER of DIW was faster than that of PJ (DIW = 18.6 ± 7.7 mL·min^{-1}, PJ = 9.9 ± 6.6 mL·min^{-1}; $F_{1,9}$ = 24.4, $P < .001$). The GERs decreased over time ($F_{4,36}$ = 23.2, $P < .001$), and the GER for the first 5 minutes of testing (52.5 ± 5.8 mL·min^{-1}) was faster than all subsequent GERs (≤ 9.6 ± 2.9 mL·min^{-1}, $P < .05$).

The GSVs did not differ over time between PJ and DIW ($F_{3,27}$ = 1.0, $P = .4$), nor were there differences between drinks ($F_{1,9}$ = 1.0, $P = .33$) or changes over time ($F_{3,27}$ = 0.4, $P = .78$). Mean GSV over the course of testing for the PJ and DIW groups was 52.6 ± 4.9 mL (range, 25.9 to 78.0 mL) and 45.2 ± 6.5 mL (range, 22.5 to 97.8 mL), respectively.

Plasma Variables

The $[Na^+]_p$ differed between drinks over time ($F_{4,36}$ = 6.2, $P < .001$; Figure 2). Baseline $[Na^+]_p$ for the PJ and DIW groups did not differ ($P > .05$). The $[Na^+]_p$ after PJ ingestion was higher than after DIW at 20 and 30 minutes postingestion ($P < .05$). The $[Na^+]_p$ after DIW ingestion was higher at 10 minutes postingestion than at baseline ($P < .05$) but returned to baseline levels thereafter. In contrast, $[Na^+]_p$ remained elevated for the duration of the experiment after PJ ingestion ($P < .05$).

Despite large changes in $[Na^+]_p$, we observed no interaction between fluids and time for calculated percentage changes in $[Na^+]$ content ($F_{4,36}$ = 0.7, $P = .61$; Figure 2) and no main-effect differences in the percentage change in $[Na^+]_p$ content for fluid ($F_{1,9}$ = 0.7, $P = .61$) or time ($F_{4,36}$ = 1.8, $P = .15$).

No interaction between fluids and time was observed for changes in PV ($F_{4,36}$ = 0.3, $P = .86$). Also, there were no PV differences between drinks ($F_{1,9}$ = 0.1, $P = .76$; Figure 2). However, PV did decrease over time ($F_{4,36}$ = 9.9, $P < .001$). Compared with baseline, PV decreased at 5, 10, 20, and 30 minutes postingestion ($P < .05$).

Nausea and Palatability

Nausea did not differ between drinks over time ($F_{4,36}$ = 1.1, $P = .36$). Although neither drink elicited strong feelings of nausea, participants reported greater overall nausea after PJ ingestion than after DIW ingestion (100-point scale: PJ = 4.1 ± 1.3 mm, DIW = 1.2 ± 1.3 mm; $F_{1,9}$ = 7.8, $P = .02$). Participants' nausea ratings increased over time ($F_{4,36}$ = 3.1, $P = .03$). Nausea was greater than baseline (0 ± 0 mm) at 10 minutes (3.4 ± 1.0 mm) and 30 minutes (3.6 ± 1.3 mm; $P < .05$). Nausea at 5 minutes (2.9 ± 1.1 mm) and 20 minutes (3.1 ± 1.2 mm) postingestion was not different from baseline ($P > .05$).

Ingesting 7 mL·kg^{-1} of DIW was more palatable than drinking similar volumes of PJ (DIW = 83.4 ± 6.2 mm, PJ = 34.0 ± 7.7 mm; t_9 = 4.2, $P = .002$). Moreover, 90% (9/10) of our participants reported gastrointestinal distress later in the day after PJ ingestion. None reported gastrointestinal distress after DIW ingestion.

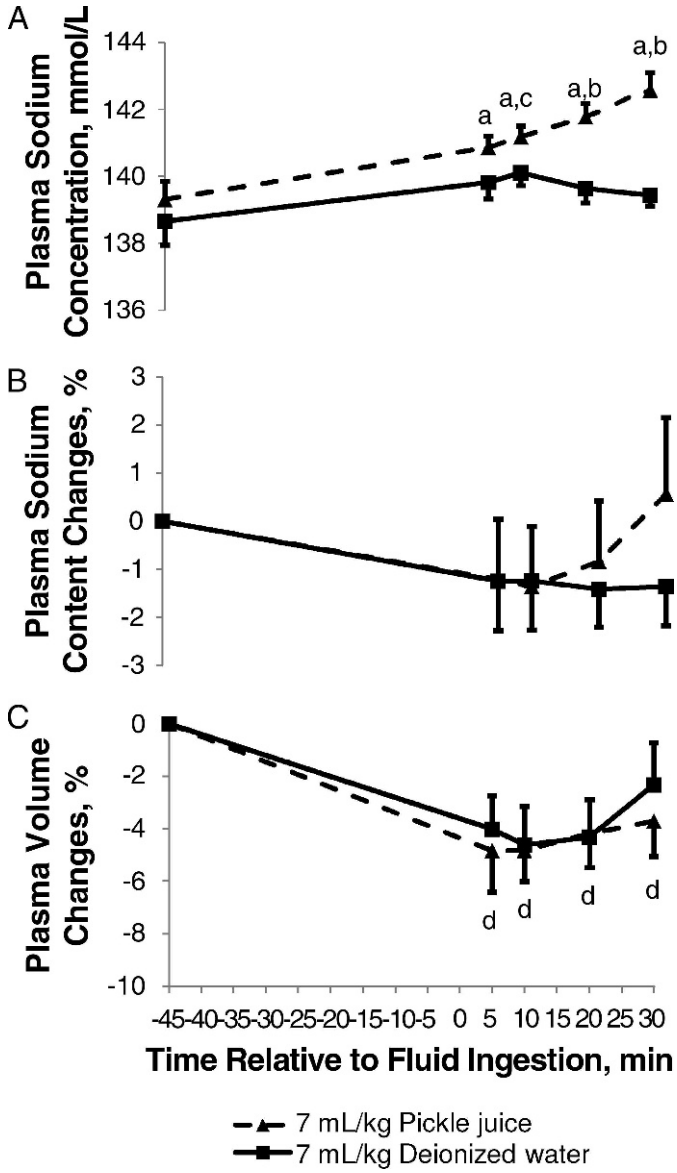

Figure 2. A, Plasma sodium concentration, B, plasma sodium content, and C, plasma volume (mean ± SE) after ingestion of 7 mL·kg^{-1} body mass of pickle juice and deionized water and changes from baseline (n = 10). [a] Indicates that plasma sodium concentration was greater at 5, 10, 20, and 30 minutes after ingestion of pickle juice than at −45 minutes. [b] Indicates that plasma sodium concentration was greater after ingestion of pickle juice than after ingestion of deionized water at 20 and 30 minutes. [c] Indicates that plasma sodium concentration was greater at 10 minutes after ingestion of deionized water than at −45 minutes. [d] Indicates that plasma volume was less at 5, 10, 20, and 30 minutes after ingestion of pickle juice than at −45 minutes. The α level was set at <.05.

DISCUSSION

Contrary to our original hypothesis, PJ and DIW did not initially differ in their GERs; with both drinks, large volumes of fluid left the stomach within the first 5 minutes postingestion (PJ = 219.2 ± 39.1 mL, DIW = 305 ± 40.5 mL). The similar GERs of the drinks can likely be attributed to an increase in gastric distension—a primary determinant of a fluid's GER.[8,13] Once this volume stimulus had dissipated, however, PJ did not empty from the stomach for the remainder of the experiment. In contrast, DIW emptied rapidly, with approximately 112 mL left in the stomach at 30 minutes postingestion.

The failure of PJ to empty from the stomach after 5 minutes postingestion is likely due to its high osmolality

(1325 ± 1 mOsm·kg H_2O^{-1}), acidity (pH = 3.2 ± 0), or both. Fluids with high osmolalities[21] and low pH[22] inhibit gastric emptying. Moreover, acetic acid, a primary ingredient in PJ, may slow gastric emptying.[9,23] Liljeberg and Bjorck[9] had participants ingest a control meal (122 g of white bread with olive oil [8 g] and cheese [23 g]) or a test meal (122 g of white bread, 23 g of cheese, and a vinaigrette sauce consisting of 20 g white vinegar, 20 g water, and 8 g olive oil). Paracetamol (1 g) was baked into the bread to allow indirect measurement of gastric emptying. Serum paracetamol concentrations were lower at 40 to 100 minutes after ingestion in postprandial men and women following the meal containing vinegar (acetic acid). The authors attributed this effect to delayed gastric emptying. However, other authors[24] have observed no changes in gastric emptying with acetic acid feedings. Fushimi et al[24] observed similar gastrointestinal polyethylene glycol concentrations in postprandial rats fed various concentrations of acetic acid in their diet (0, 0.1, 0.2, or 0.4 g acetic acid per100-g diet). Differences in these observations may reflect differences in experimental protocols used to determine gastric emptying, concentrations of acetic acid infused or ingested by participants, and other solutions or foods ingested concurrently with acetic acid. We could not find any published research on the effects of ingesting various volumes of liquid acetic acid on gastric emptying.

Maintenance of gastric volume during the PJ trials cannot be attributed primarily to an increase in GSV. Although hypertonic solutions tend to increase gastric secretions,[25] we did not observe any differences in secretions after PJ or DIW ingestion. Therefore, the GER differences between PJ and DIW are best explained by differences in drink composition.

To confirm that the rapid decrease in GER after PJ ingestion was likely due to gastric distension, we performed a pilot study in which 3 participants from the original experiment repeated the study a third time but ingested a smaller volume of PJ (2 mL·kg^{-1} body weight: 152.3 ± 15 mL). Initial GV in this trial was 226.5 ± 22.2 mL. As hypothesized, when participants ingested smaller volumes of PJ, less PJ emptied from the stomach during the initial 5 minutes postingestion (40.9 ± 12.8 mL; GER during the first 5 minutes was 8.2 ± 2.6 mL·min^{-1}). After this brief period of emptying, GV increased over the next 15 minutes (range, 221.6 ± 41.2 mL to 234.4 ± 39.9 mL at 10 and 20 minutes postingestion, respectively). This increase was likely due to gastric secretions (mean gastric secretion = 36.3 ± 5.1 mL; range, 26.0–41.8 mL). Final gastric volume at 30 minutes postingestion for this trial was 162.9 ± 28.4 mL. This pilot work tentatively confirms the volume stimulus observed in the 7 mL·kg^{-1} body-weight trial.

The nature of GV measurement prohibited us from determining the amount of PJ that emptied within the first minute of ingestion in both the 7 mL·kg^{-1} and 2 mL·kg^{-1} trials. However, GERs for the 2 mL·kg^{-1} and 7 mL·kg^{-1} PJ trials during the first 5 minutes postingestion indicate that approximately 8 to 10 mL, respectively, of PJ would have emptied from the stomach within the time periods described for cramp alleviation (ie, <60 seconds).[5,6] Assuming our participants had a total-body exchangeable sodium content of 2828 mmol (extracellular space volume estimated from body mass, $[Na^+]_p$ taken from the baseline blood sample), these 8 to 10 mL of absorbed PJ would have contributed only 7.5 to 9.3 mmol of new sodium to the extracellular space. Thus $[Na^+]_p$ would have increased by only 0.32 to 0.39 mmol·L^{-1}.

Assuming EAMC are associated with electrolyte imbalances, these hematologic changes are unlikely to have a clinical effect on acute EAMC, considering that plasma sodium losses in these athletes can be up to 87 mmol·h^{-1}.[26] Therefore, if health care professionals provide small volumes of PJ to athletes experiencing EAMC, most of the ingested PJ is likely to remain in the stomach for several minutes after ingestion, and the small volume that may be absorbed is unlikely to have a significant effect on extracellular sodium content. Based on these facts, it is doubtful that sodium changes could relieve EAMC.

Ingesting large volumes of PJ resulted in increases in $[Na^+]_p$ over the course of the study. Health care professionals have warned that ingesting PJ without concurrent hypotonic fluids could contribute to dehydration-induced hypertonicity and delay rehydration.[27] Although ingesting large volumes of PJ did cause substantial increases in $[Na^+]_p$, these increases were due to rapid decreases in PV rather than an increase in actual plasma sodium content. Thus, despite a large bolus of hypertonic fluid being delivered to the small intestine (approximately 219 mL within the first 5 minutes postingestion), little of the sodium in PJ was actually absorbed and assimilated into the extracellular-fluid compartment. Because these changes occurred after ingestion of both fluids, it appears that gastric distension, rather than fluid composition, triggered cardiovascular reflexes that resulted in transient PV decreases. Some cardiovascular reflexes have been shown to be drinking-mediated responses to large boluses of fluid rather than a response to fluid composition (eg, the fall in plasma arginine vasopressin after hypertonic saline ingestion).[28] Moreover, other authors[29] have observed transient decreases in PV after ingestion of large boluses (355 mL) of hypertonic and hypotonic fluids. Johannsen et al[29] observed 2% to 4% reductions in PV 45 minutes after chicken noodle soup (167 mmol·L^{-1}) and water ingestion in rested, mildly hypohydrated participants. The small PV losses observed by us and others[29] could reflect a reflex, triggered by gastric distension, in which hypotonic fluid is shifted out of the intravascular space to aid in the absorption of the ingested fluids. Alternatively, the 45 minutes of rest before subsequent blood testing may have also played a role in the small changes in $[Na^+]_p$ and PV observed after ingestion of PJ and DIW. Further research is needed to clarify this observation.

As expected, participants preferred drinking large volumes of DIW over PJ. This is likely due to PJ's high sodium content and acidity. Humans have an increased preference for sodium after exercise,[30] and eunatremic participants tend to have a greater aversion to high quantities of sodium.[31] Moreover, humans have a general aversion to sour taste stimuli.[32] Because our participants were euhydrated, eunatremic, and rested upon drink ingestion, their preference for sodium was likely low, thereby resulting in lower palatability ratings after PJ ingestion. Because EAMC typically occurs during or shortly after exercise,[33] athletes experiencing EAMC may have a greater tolerance for PJ due to exercise-induced sodium losses. Data verifying this assertion are lacking, however.

Despite drinking a large volume of PJ, participants were not extremely nauseated over the course of the study. However, most of our participants reported gastrointestinal distress sometime after the 7 $mL \cdot kg^{-1}$ PJ trial. This is likely due to the unabsorbed sodium osmotically drawing hypotonic fluid into the gastrointestinal tract.[34] Therefore, if health care professionals provide PJ to athletes, they should do so in small volumes.[7] Preliminary data from our pilot study tentatively confirm this recommendation, because none of our pilot study participants experienced gastrointestinal distress after testing. We do not advocate ingesting large quantities of PJ; however, if larger volumes of PJ are provided, the athlete should ingest copious volumes of hypotonic beverages concomitantly.[27] This may help prevent gastrointestinal distress.

Given that the GER of small volumes of PJ is slow, we believe these data support our theory that PJ ingestion does not relieve skeletal muscle cramps via a metabolic mechanism (specifically, restoration of $[Na^+]_p$ or PV).[6] However, before a metabolic effect of PJ can be completely ruled out, future researchers should focus on the absorption of ingredients other than electrolytes[4,7] in PJ that may be responsible for cramp alleviation. For example, anecdotal support exists for the ingestion of acetic acid (vinegar) to rapidly relieve EAMC.[35] Moreover, some authors[36–38] have observed that acetate appears rapidly in the bloodstream after ingestion, causing speculation that it may be absorbed through the stomach lining.[36] Acetate could, theoretically, provide substrate for anaerobic metabolism.[39] If EAMC is due to fatigue as theorized,[40] an increase in anaerobic metabolism and, consequently, adenosine triphosphate may relieve EAMC. Future investigators should examine changes in blood acetate levels after vinegar or PJ ingestion.

Finally, we must acknowledge that our participants were euhydrated and eunatremic during testing. The available literature on PJ ingestion suggests that PJ is most often given to hypohydrated, exercised individuals[5,6] rather than euhydrated, rested, and eunatremic individuals. We designed our experiment in this manner to increase its internal validity. Both exercise[16,41] and hypohydration[42] can negatively influence the GER of a fluid. If we had added these variables, we might have confounded the results of our original research questions. Therefore, we sacrificed some external validity to understand how quickly PJ leaves the stomach under ''optimal conditions'' for fluid emptying. Investigating PJ's GER in exercised, hypohydrated individuals does warrant further study.

In conclusion, large volumes of PJ and DIW had similar GERs shortly after ingestion, which is likely due to gastric distension. The GER indicates that small volumes of PJ left the stomach in the time frames that health care professionals describe for EAMC alleviation. The slow GER of PJ probably reflects its composition. The increase in $[Na^+]_p$ after PJ ingestion is likely the result of gastric distension triggering cardiovascular reflexes, which caused a shift of hypotonic fluid out of the intravascular space. Despite ingesting more than 500 $mmol \cdot L^{-1}$ of sodium with PJ, $[Na^+]_p$ content remained unchanged for the majority of the experiment. Overall, these data support our initial theory that PJ may relieve skeletal muscle cramps by a neurologic or other unknown metabolic mechanism. Future researchers should focus on the effects of acetic acid ingestion on muscle-cramp alleviation and changes in plasma acetate concentrations after PJ ingestion to further rule out possible metabolic mechanisms of cramp alleviation.

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