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Effects of a Ketogenic Diet Intervention on Affective Valence in Masters-Level Athlete: A Case Study

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Abstract: *The Ketogenic diet (KD) has become extremely popular in the last decade. A KD appears to have considerable therapeutic utility, reduces weight, and enhances athletic performance. In particular, improving performance in distance runners is driving many runners to try KDs. As such, the present experiment had two aims: a) quantify whether a KD intervention alters global and exercise-specific affect and when these changes occur, and b) determine if bone mineral density is changed. One elite masters-level runner (male, 64) was assessed for 2 weeks on a standard diet (SD), and at multiple time points during a 6-week KD intervention. There were reductions in both global positive and negative affect. Physical activity-specific positive affect increased from the SD condition, while negative affect, tranquility, and fatigue were reduced. Bone mineral density was down nearly 1% after the intervention.*

Keywords: *Affect, Bone Mineral Density, PANAS, PAAS*

1. INTRODUCTION

The ketogenic diet (KD) has been promoted as a quick way to lose weight and has gained international popularity over the last decade. With this rise in popularity has come an increase in research. Much of the research on KDs has focused on the diet as a primary or adjuvant therapy for neurological disorders, as it was originally developed for children with intractable epilepsy (Wheless, 2008). More recently, research has been done on exercisers and athletes from various backgrounds. The results are mixed, and the literature lacks studies directly assessing changes in affective valence inathletes. Additionally, there is a suggestion that the KD harms bone health (Heikura et al., 2020), but no research has been done with runners. The current study fills a research gap by examining both affect and bone health changes due to a KD.

A KD involves a rather unconventional macronutrient profile by modern standards. In a typical 2,000 kcal/day KD, 70% of the total calories come from fats, 20% from proteins, and 10% from carbohydrates. In clinical applications to control epilepsy, fat is kept near 90% and protein is capped at 1 g/kg/day, with carbohydrates consistently held between 20 and 50 grams per day (Meira et al., 2019). When carbohydrates are kept low or prolonged fasting/starvation occurs, a series of biological and chemical changes take place to adjust for the lack of glucose availability. As a result of the carbohydrate reduction, there is an upregulation of the fatty acid oxidation pathways, a downregulation of glycolytic pathways, and increased reliance on hepatic gluconeogenesis. The body must then rely on fat as the primary fuel source, leading to increased β-oxidation in the liver, which produces Acetyl-CoA to generate ATP.

Many effects of KDs are neurological and psychological. As noted earlier, the KD was developedfor intractable epilepsy, but more work is being done on other diseases. AKD has helped patients with Parkinson’s and Alzheimer’s by reducing motor symptoms and improving memory and cognition (Lange et al., 2017; Phillips et al., 2018). The underlying mechanisms are poorly understood but may be linked to improved mitochondrial efficiency and decreased glycolytic flux (Włodarek, 2019). When KDs are tested in individuals with major depressive disorder, the KD appears to improve symptoms and mood (Włodarczyk et al., 2021). KDs seem to be positively correlated with increases in the inhibitory neurotransmitter gamma aminobutyric acid (GABA), and potentially the regulation of circulating glutamate, creating a more favorable GABA:glutamate ratio (Yudkoff et al., 2007). Low levels of GABA are associated with depression. In contrast, elevated glutamatemay be associated with anxiety and depression at slightly elevated levels (Sanacora et al., 2003). In brief, KDs increasing GABA and decreasing glutamate may play a role in reducing depression.

In healthy populations, however, there appears to be a decrease in motivation to exercise and increase in perceived exertion and irritability when subjects are placed on a 2-week hypocaloric KD intervention (White et al., 2007). Crossfit-trained athletes reported increased irritability, drowsiness, and changes in mood during the first week of a 4-weekKD intervention. This led several participants to drop out of the study (Durkalec-Michalski et al., 2019). Trained female cyclists reported increased tension, depression, anger, and decreased vigor when placed on a 1-week KD. These adverse changes in affect may be due to carbohydrate dependence, or a result of other systemic changes occurring as the body adapts reduced carbohydrates. A shortcoming of these is they are all very short-term studies.

Longer-term studies evaluating the psychological outcomes of a KD are scarce, but anecdotal reports and researchers suggest negative affect changes may be short-term. A 6-week KD intervention with powerlifters found that the only significant change was a significant decrease in anxiety in the KD group (Thorp, 2015). Both the control and KD groups also significantly improved their bench press, squat, and deadlift performance suggesting that a KD may not necessarily be detrimental to strength sports, as is often suggested. A year-long study comparing a KD to a low-fat diet found greater decreases in negative affect as well as feelings of hunger in the KD group versus the low-fat group (McClernon et al., 2007). There was a trend towards lower fatigue in the KD group, but this result did not reach statistical significance. A one-year study comparing an energy-restricted low-carb diet to an isocaloric low-fat diet found a significant time x diet interaction for total mood disturbance, anger-hostility, confusion-bewilderment, and depression-dejection. The low-fat group saw greater sustained improvements while the low-carb group saw initial improvements in these domains before rebounding to near-baseline (Brinkworth et al., 2009).

The discomfort that athletes report experiencing when switching to KDs is a multifactorial problem involving the acute depletion of glycogen, diuresis resulting in poor hydration and electrolyte balance, and a host of metabolic changes taking place as the body adjusts to the diet (Dhamija et al., 2021; Phinney, 2004) . As a result, exercise may become an unpleasant experience while in the adaptation phase. Exercise psychology research has a long history of establishing a dose-response relationship between exercise and improved feelings or affect, but this relationship is complex. In a narrative review, Ekkekakis and Brand (2019) note that there is considerable interindividual variation in affective responses to exercise, and it is rarely as unidimensional as lab-based research makes it seem. So while exercise should improve affect, particularly in trained athletes, the unpleasantness experienced in the adaptation phase of the KD may be at least partially responsible for a loss of motivation to continue exercising.

Given the lack of evidence on how longer term KDs change global and sport-specific affect in athletes, the current study seeks to quantify where and when affect changes occur during KD adaptation. The rationale for global and sport-specific affect is threefold. First, because the participant is a runner, the effect of a KD on sport-specific affect is a point of interest. Second, this will also help identify whether the KD and physical activity induces affective changes generalized to global affect during work or leisure time. Third, anecdotal reports suggest a KD influences negative affect, but it is unknown if positive affect is also influenced.

One additional notable but under-researched adverse side effect of the KD appears to be degradation of bone- an effect noted as far back as the 1970s where bone mass was found to be decreased in children receiving a KD intervention (Hahn et al., 1979). More recent studies are less clear. Bergqvist and colleagues found that over a 15-month KD intervention, children treated for intractable epilepsy saw sharp declines in bone mineral content (BMC) over the duration of the intervention (Bergqvist et al., 2008). In contrast, a 5-year longitudinal KD case study on 3 adult patients with Glucose Transporter 1 (GLUT-1) Deficiency Syndrome foundno significant changes in BMC, BMD, or body composition that occurred (Bertoli et al., 2014).

Researchers studying the KD often use small sample sizes and utilize participants with underlying health conditions who may also be on medication. Recent work has examined bone mineral density and athletic performance in healthy adults and athletes. Research in Australia examined a KD intervention on world-class race. The results after 3.5 weeks on a KD indicate that in this highly trained cohort, the marker for bone breakdown (CTX) was elevated above baseline, while markers for bone formation and metabolism (P1NP and OC, respectively) were decreased, suggesting BMD loss was occurring (Heikura et al., 2020). Given the dependence most athletes have on carbohydrates and the dramatic change required to move to a KD, this 3.5 week time frame may be insufficient for full adaptation to occur. Indeed, earlier works attempting to better understand the KD adaptation period noted that, while there appears to be a performance decrement in the first couple of weeks, a gradual rebound begins to occur (Phinney et al., 1980). These researchers noted that glycogen stores also recovered to near-baseline with subjective exhaustion during exercise increasing to 155% of baseline performance after 6 weeks.Other researchers have found glycogen utilization and storage is not significantly different between low-carb and high-carb athletes after a 180-minute run (Volek et al., 2016).

The exact cause of BMD loss due to KDs is still poorly understood, but it may be caused, at least in part, by chronic metabolic acidosis. This acidosis is inherent to KDs, as the three ketone bodies (BHB, acetoacetate, and acetone) are acidic. The generally accepted standard for being in a state of ketosis is a blood measurement >.5 mMol (Kanikarla-Marie & Jain, 2016), as it is at least a 2-fold increase over normal ketone concentration. In ketosis, homeostatic mechanisms rely on buffers to control systemic pH. This chronic acidosis may lead to conditions that generate a loss of bone mineral ions due to buffering from skeletal tissue in the absence of sufficient buffering agents. Additionally, a decrease in the conversion of 25-hydroxy-vitamin D to its active metabolite in the kidney can lead to BMD loss (Sampath et al., 2007). In summary, there is insufficient literature on whether KDs have a clinically significant impact on BMD and how it altersglobal and sport-specific affective valancein athletic populations and whether. The present study aims to fill these gaps.

2. METHODS

2.1. Participant

This case study consists of one highly trained, elite-level masters runner. The participant is a 64-year-old Caucasian male who has participated in high-level marathon races (e.g., world championships) for the last 45 years. He has never tried the KD and otherwise consumes a standard Western diet (SD).

2.2. Research Design

Physiological and Performance Data

2.2.1. Bone Mineral Density (BMD)

BMD was assessed by Dual-energy X-ray Absorptiometry (DXA) by a Hologic Horizon A scanner, Software Version 13.6.0.5 with TBAR1209 NHANES BCA calibration. This was conducted at Weeks 2 and 8 to determine a baseline on SD and changes at the conclusion of the intervention, respectively. Some BMD and BMC loss was anticipated by the second week of the KD (Ding et al., 2019; Heikura et al., 2020). Whether this would continue through the adaptation period was unclear and no a priori hypothesis was provided.

2.2.2. Blood Glucose and Ketones

Fasting blood glucose and ketones were analyzed by a Keto-Mojo monitor, previously shown to provide valid and reliable measurements of nutritional ketosis and blood glucose (Moore et al., 2021). Blood glucose on SD should fall in the normal range of 80 to 130 mg/dl given the participant’s health and training status.

2.2.3. VO2 Max

VO2 max was assessed using a peak-speed treadmill protocol (Scrimgeour et al., 1986)on Lode Valiant Sport treadmill with Parvo Medics True One 2400 Metabolic Measurement System, version 4.3.4. This was collected at weeks 2 and 10 to assess changes in performance, substrate utilization, peak O2 and CO2 exchange, total time, and distance to exhaustion.

2.2.4. Rating of Perceived Exertion (RPE)

RPE for weekly runs and VO2 max tests were measured on the Borg RPE Scale. The scale ranges from 6 to 20, where 6 is no exertion (as in sitting/resting) and 20 is maximum exertion. The Borg RPE scale produces valid and reliable scores for estimating heart rate and work intensity(Chen et al., 2010; Stamford, 2007).

2.3. Psychological Measures

We measured sport-specific and global affective response. The data for sport-specific affect will help elucidate whether the KD influences affect while running. Potential changes to global affect in his day-to-day life will determine if life outside of training is influenced. Anecdotal data suggests that the KD influences negative affect, such as increasing irritability. It is unknown whether this will also influence positive affect, as affective valence does not have a direct inverse relationship. For example, there can be an increase in negative affect (e.g., becoming more irritable) without seeing a change in positive affect.

2.3.1. Global Affect

Changes in global measures of affect were assessed by the Positive and Negative Affect Schedule (PANAS). PANAS consists of two 10-item scales: negative and positive affect. PANAS produces scores found to be reliable and consistent, with a Chronbach's α of .90 for positive affect and .87 for negative affect (Watson & Clark, 1988). An example item from PANAS is "Jittery" measured on a 5-point Likert scale ranging from 1 (not at all) to 5 (extremely) (Watson & Clark, 1988).

2.3.2. Physical Activity Affect

The Physical Activity Affect Scale (PAAS) was used to determine sport-specific affect. PAAS consists of 12 single-adjective items across 4 subscales: positive affect, negative affect, fatigue, and tranquility (Lox et al., 2009). For example, one adjective is "Relaxed," with responses for each item ranging from 0 (do not feel) to 4 (feel very strongly). This scale has been found to produce scores considered to be valid and reliable, with positive affect, negative affect, fatigue, and tranquility having a Chronbach's α of .94, .86, .91, and .84, respectively (Lox et al., 2009). Physical activity affect was assessed weekly during the 10 km run, beginning in the last 2.5 km.

2.3.3. Center for Epidemiologic Studies Depression Scale- Revised

The Center for Epidemiologic Studies Depression Scale- Revised (CESD-R) ensured the participant was not depressed at the onset of the study. It was used at multiple timepoints through the intervention to evaluate if the KD had any impact on depression scores. The CESD-R has been found to provide scores considered to be valid and reliable for diagnosing depression in the general population (van Dam & Earleywine, 2011).

Baseline nutrition, performance, and physiological data were collected during a 2-week SD, followed by a 6-week KD. Calories and protein were held constant when switching from the SD to a KD, with the only adjustments being fat and carbohydrate content. Training volume and intensity were assigned to be approximately identical between both diets to avoid the influence of physical activity (PA) on body composition and BMD. Training volume and intensity were tracked by GPS and effort was determined subjectively and objectively. To detect changes in affect, psychological survey data was collected weekly for both SD and KD.

Weekly submaximal 10-kilometer runs were conducted with PA affect data collected at the same time. The weekly 10-km run was performed on an indoor treadmill and the affect data was collected in the final 25% of the run. Submaximal effort was based on ventilatory gas exchange threshold derived from VO2 max data. Fasting blood measurements were taken weekly to track changes in glucose and ketone concentrations. VO2 max and DXA scans took place during the SD period and at the conclusion of the KD intervention. Weekly affect surveys were administered prior to blood and performance testing and used to determine changes in overall affect.

Several physiological parameters were assessed during the SD period. A VO2 max test was performed to determine current cardiovascular fitness and repeated at the conclusion of the KD intervention. Blood glucose, ketones, and urinary contents were assessed while in a fasted state. Baseline body weight was tracked, and body fat, lean mass, and BMD was determined by DXA at the end of the 2-week SD period and again at the end of the KD. A timeline of the events is laid out in Graph 1.

Baseline nutrition data was collected daily for the 2-week SD period to determine average daily calories and macronutrient composition (i.e., grams of protein, fats, and carbohydrates). Because 24-hour recall food frequency questionnaires are inaccurate, food data was collected by weighed food record, then put into nutrition app (i.e. Cronometer) in order to determine macro- and micronutrient distribution and average calories consumed daily. Cronometer utilizes a number of databases such as the U.S Department of Agriculture National Nutrient Database for Standard Reference (USDA SR28), leading to highly accurate nutrient tracking when paired with a food scale and weighed food record (*Data Sources – Cronometer*, n.d.).

3. ANALYSIS

For this case study, data are presented graphically and inspected visually. Changes in BMD are presented as Z- and T-Scores.

4. RESULTS

4.1. Blood Glucose and Ketones

During the SD, blood glucose average was 103 mg/dl and average blood ketones were .3 mmol. After 24 hours on the KD, the participant had exceeded the threshold value for ketosis, reaching .6 mmol in the first day. Self-testing of ketones was conducted between weekly test and values ranged from 8.8 mmol at the end of the first week to as low as .6 mmol near the end of the intervention. For the duration of the intervention, levels remained consistently above the .5 mmol threshold for ketosis, though significant fluctuations occurred. Blood glucose also remained stable for the duration of the KD, ranging from 108 ng/dl during the SD to 91ng/dl during the KD.

4.2. VO2 Max

Baseline VO2 max testing provided an absolute value of 3.03 L/min and a relative VO2 max of 47.99 mL/kg/min. Follow up testing at the end of the of the KD intervention showed an increase in relative VO2 max to 48.72 mL/kg/min, with absolute VO2 max remaining near the baseline value at 3.01 L/min.

4.3. RPE and Heart Rate

RPE varied between 12 and 14 but remained unchanged between the SD and KD periods. Average heart rate during 10-km testing in the SD period was 129 bpm, rising slightly to 131 during the KD. Maximum heart rate also had a similar result. During the SD period, a max HR of 167 bpm was achieved just prior to stopping the test, which was 107% of the participant's age-predicted heart rate maximum. In the KD period, a max HR of 170 was achieved (109% of age predicted heart rate maximum).

4.4. DXA Results

Despite the isocaloric nature of the KD intervention, total body fat was reduced by .94kg after the intervention. Total lean mass was reduced by .03kg, consistent with evidence that circulating ketones have a muscle-sparing effect. In total, a 1.2% reduction in body fat occurred over the 6 week intervention. Total bone mineral density was reduced by .009 g/cm^{2}from the baseline value of 1.167 g/cm^2 for a .8% loss in BMD. T-Score was also lowered from -0.3 at baseline to -0.4 after the KD intervention. Z-Score followed a similar pattern, dropping from 0.1 at baseline to 0.0 after the KD. BMD summary is provided in Figure 6.T-Scores compare the subject's bone density to that of a healthy30-year oldmale, while Z-Scores compare the subject's bone density to that of an average person of the same age and sex. The current Z-Score suggests the participant still has average BMD for his age.

4.5. Psychological Variables

4.5.1. Global Affect

Both item-level and scale-level results were calculated. Item-level visualization showed little change over time in negative affect with greater variation in the positive affect items. (See Figure 1)

At the scale level, the overall trend followed patterns at the item level. Positive affect follows a steady decline into the 6th week before beginning to return towards baseline. By the end of the intervention, Positive affect had not fully recovered to SD levels. Negative affect also declined slightly beginning when the KD began and continuing for the duration of the intervention. This increased slightly in the 6th week, but negativeaffect remained reduced throughout the KD.

Table1. *PANAS and PAAS Scale Score Results, Mean Changes, and Standard Deviations*

PASS Scale Scores					
	M			**SD**	
	SD	**KD**	**Mean Change**	**SD**	**KD**
Positive	7.5	7.6	0.1	0.5	1.85
Negative	4.5	4.2	-0.3	1.5	0.98
Fatigue	7.5	5.8	-1.7	1.5	2.48
Tranquility	8.5	6.2	-2.3	1.5	1.6
PANAS Scale Scores					
	M			**SD**	
	SD	**KD**	**Mean Change**	**SD**	**KD**
Positive	39	35	-6	0.5	5.6
Negative	14	11	-3	0	1.4

4.5.2. Physical Activity Affect

The participant was given the PAAS questions at the 7.5-kilometer mark of a 10-km run, with no pause to allow for changes in affect relating to rest. Items were analyzed together under their appropriate scale in addition to overall scale-level changes. (See Figure 3).

Scale-level analysis, depicted in Figure 3, showed that during exercise, positive affect increased after starting the KD, while negative affect, tranquility, and fatigue decreased. This trend runs counter to the downward trend in PANAS global positive affect.

5. DISCUSSION

These data reveal a novel effect of a KD intervention on an elite masters-level runner. Much "anecdata" exists amongst athletes who have experimented with KDs,however there is little peer-reviewed literature. This study provides evidence of affective changes resulting from a 6-week KD intervention. Specifically, this study demonstrates that in day-to-day life, positive and negative global affect both decreased. In addition, during PA, positive affect increased, while negative affect, tranquility, and fatigue decreased.

An interesting trend emerged in the PANAS positive affect item analysis. Beginning around the 4th week of the KD intervention, several positive affect items scores began declining for approximately 2 weeks before beginning to rebound. This followed a trend in the participant's blood ketone levels. At the onset of the KD, blood ketone levels rose rapidly. Within the first 24-hours, the participant was already in a state of ketosis, with a blood ketone reading of .6 mmol. Six days after that reading, the participant's blood ketone reading had risen to 8.8 mmol. A range of .5 to 3 mmol is generally considered optimal, with fluctuations as high as 5.0 in cases where a prolonged fast is followed by exercise. Exceeding 8.0 mmol is within the realm of ketoacidosis in a non-diabetic person, so the participant immediately increased carbohydrate intake. Approximately two weeks after the instruction to consume more carbohydrates, blood ketones had dropped down to the lower threshold of .5 mmol, where the decrease in measures of global positive affect began as well. Once blood ketone levels began rising closer to 1.0 mmol and beyond, positive affect measures began increasing as well.

These findings suggest that there may be an optimal level of ketones to maintain or improve positive affect when on a KD. Given the rapid adaptation for this particular athlete, this also provides evidence that the normal recommendation of 2 to 4 weeks of adaptation time may not be applicable to experienced runners. Because the participant has over 50 years of distance running experience, the accompanying physiological changes that enable greater fatty acid oxidation may have helped accelerate the adaptation to a KD. This rationale may also partially explain why the participant defied the anecdotal observation that a more significant adverse change in PAAS and PANAS scores would occur in the first couple of weeks while adapting to a KD. This affect change appeared later than expected potentially due to the expedient adaptation, but allowing too many carbohydrates into the diet after adaptation lowered the circulating levels of ketone, adversely altering positive affect.

The rise in positive affect with the reduction in negative affect, tranquility, and fatigue during exercise indicates that there may be a benefit to exercise-related affect in those who adapt to the diet quickly. Interestingly, this defied the hypothesis that affect would become less positive and more negative resulting from the KD intervention. This may again be due to the favorable adaptations for fatty acid oxidation associated with decades of long-distance running.

Reductions in fatigue during exercise may present a positive argument for runners utilizing ketosis in submaximal effort runs. Given that ratings of perceived exertion were similar during the SD and KD VO2 max tests with similar METs between conditions (SD: 13.7 METs, KD: 13.9 METs), it is unclear whether other athletes placed on a KD would report the same reduction or if their scores would remain similar between KD and SD conditions.

Reduced tranquility was the most significant change among the four PAAS subscales. It is possible that despite the decrease in fatigue reported on the subscales, at some level exercise felt more challenging on the KD than on the SD. This could potentially lead to reductions on the items calm, peaceful, and relaxed as well as the overall tranquility subscale score. Interestingly, the participant's subjective accounts of this experience both on the Borg RPE scale and in verbal questioning did not reflect any feelings of increased difficulty while on the KD. It is also possible that an injury (reported in Limitations) may have influenced this value. The participant had just started to recover from a musculoskeletal injury which could explain the significant drop in tranquility in the latter 4 weeks of the KD, with a sharp increase on the final day possibly being related to nearing 100% recovery.

6. LIMITATIONS AND STRENGTHS

This single-subject case study has several limitations. Shortly after the onset of the study, the participant incurred a lower body injury (unrelated to the protocol) which hampered training efforts. The injurynecessitated a shift to less running and more elliptical and bike-based training, keeping total minutes of cardio similar each week. However, the injury may have influenced the psychological and physiological outcomes. While ketones were tracked nearly continuously for the duration of the intervention, time off to recover from the injury led to large gaps in the survey data and fewer submaximal running tests than desired. Additionally, given the athlete in this case study has performed at an elite level for decades, these results are not generalizable to all runners. Bone mineral density changes may have been exaggerated given that peak BMD occurs around 30 years of age and declines thereafter. Despite the limitations, the current study adds to the literature in three ways. First, it is one of the first studies to examine global and exercise-specific affect. Second, it is one of the first to examine both positive and negative affect. Third, it also addresses the lack of research on bone density. The research design and findings in all three of the aforementioned areas provide a roadmap and preliminary results to guide future research.

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APPENDIX

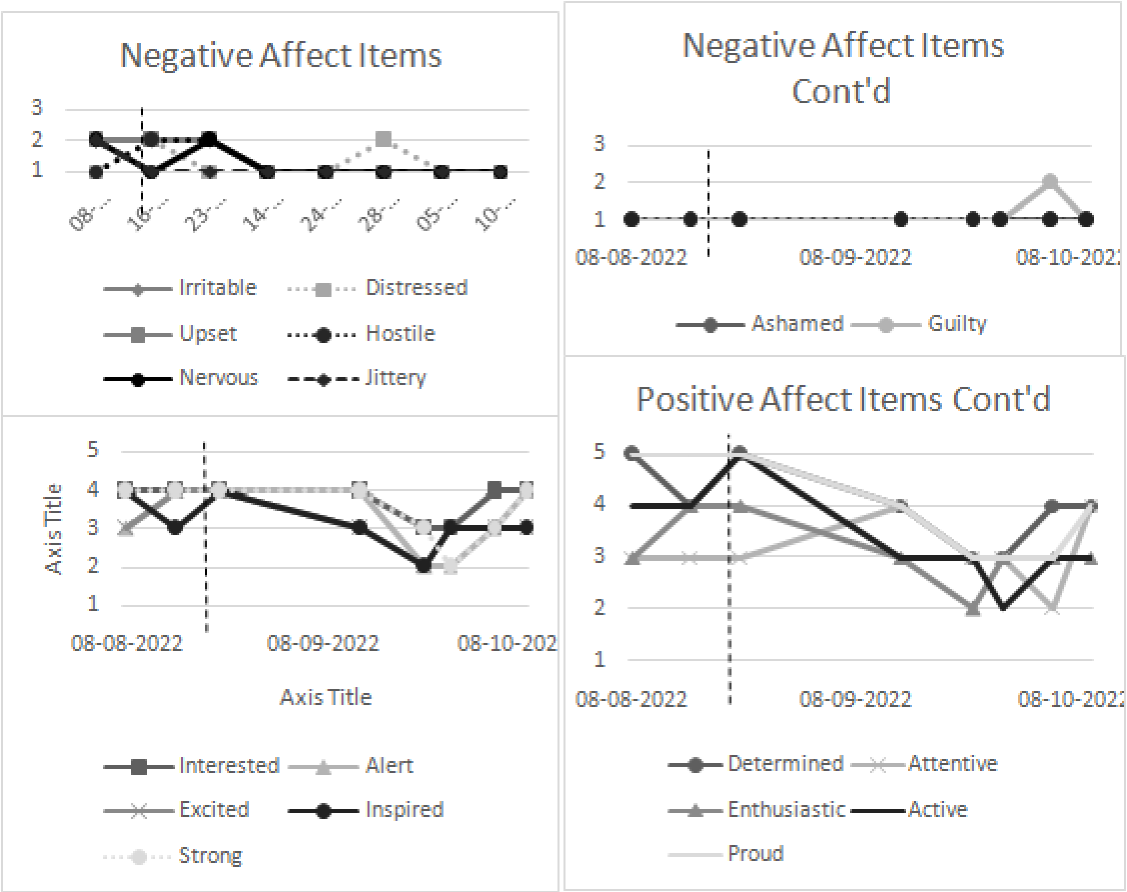


Figure1. *Positive and Negative Affect Item Scores from PANAS*

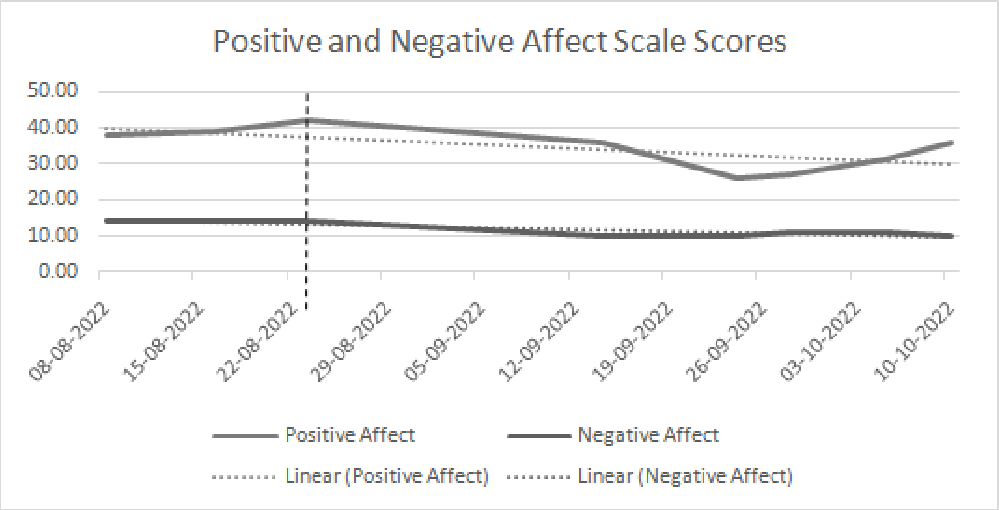


Figure2. *PANAS Positive and Negative Affect Scale Change Over Time*

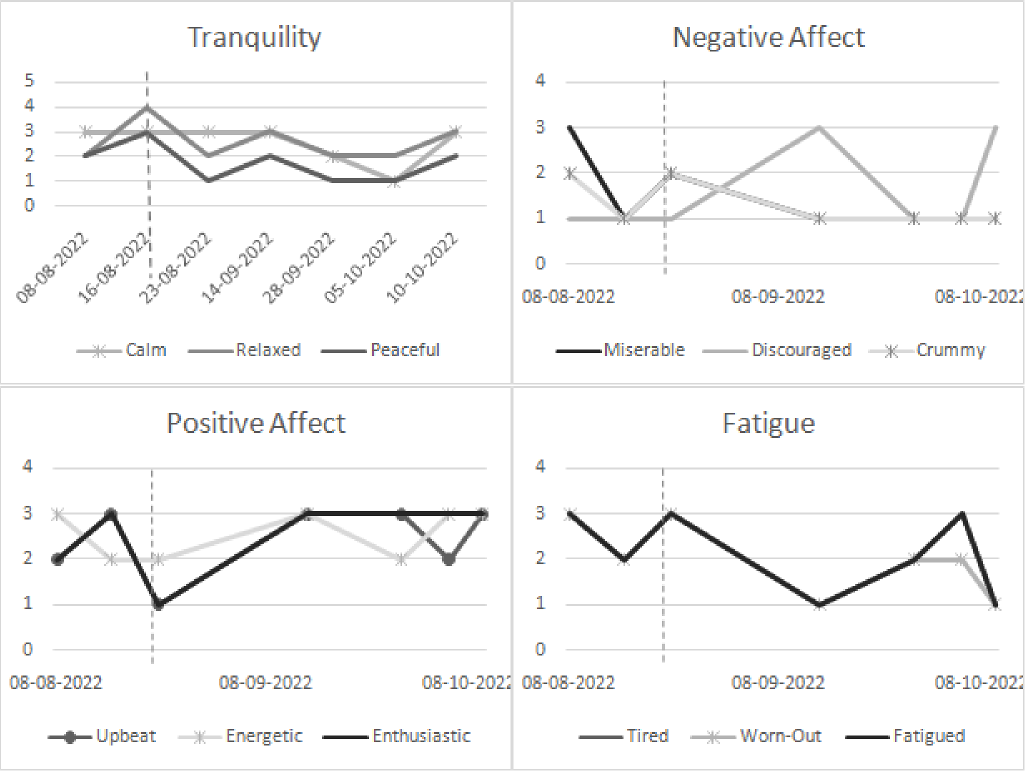


Figure3. *PAAS Item Scores for Tranquility, Negative Affect, Positive Affect, and Fatigue*

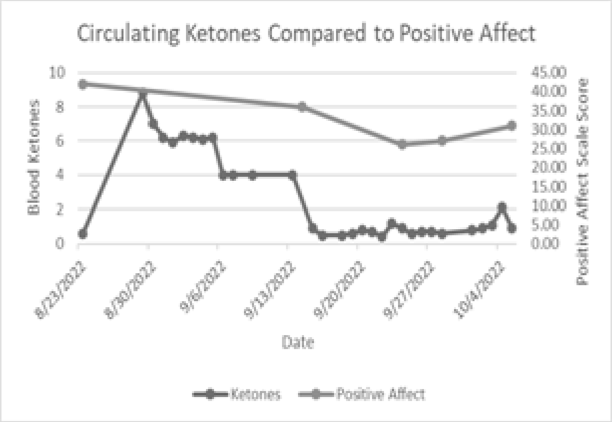


Figure4. *Relationship between circulating ketones and positive affect during exercise*

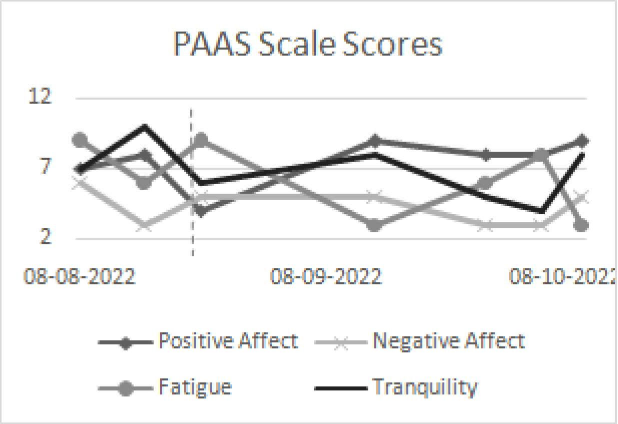
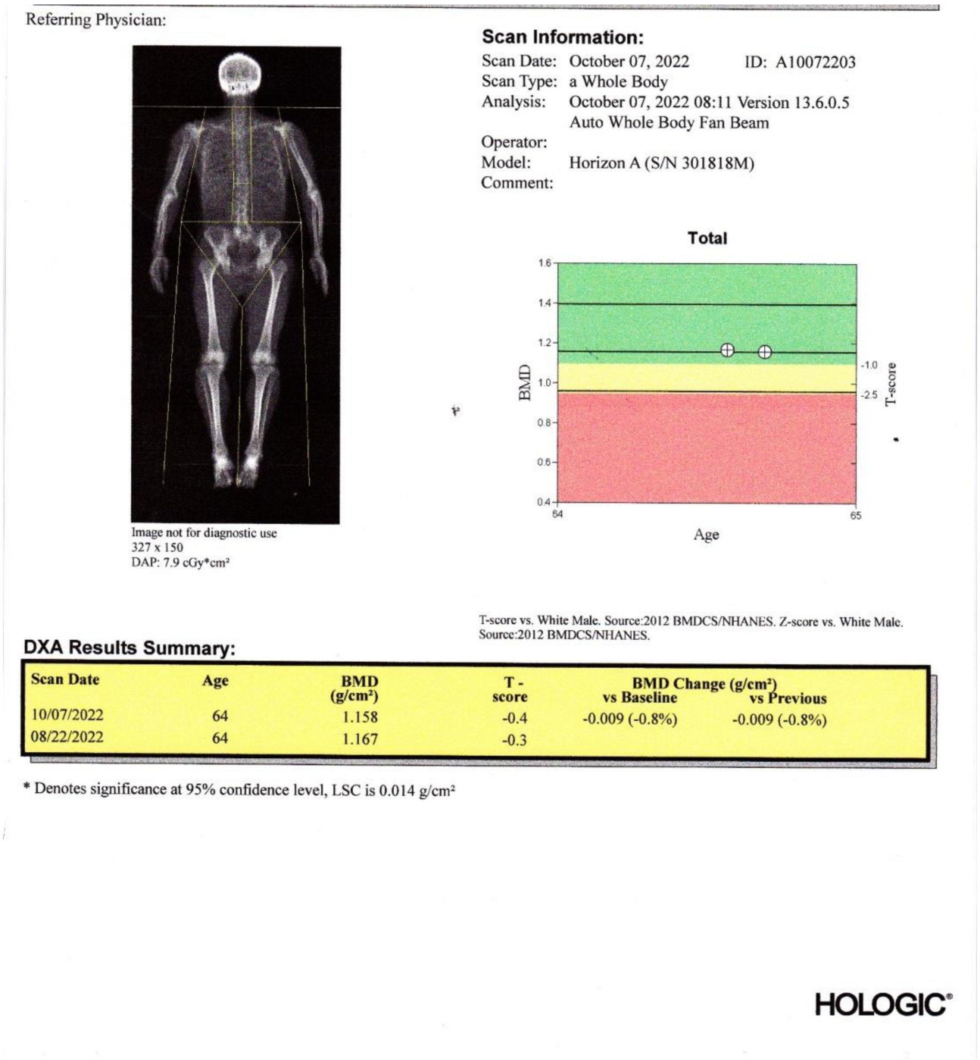


Figure5. *PAAS scale-level changes over time*



Referring Physician:

Scan Information:

Scan Date: October 07, 2022 ID: A10072203
Scan Type: a Whole Body
Analysis: October 07, 2022 08:11 Version 13.6.0.5
Auto Whole Body Fan Beam
Operator:
Model: Horizon A (S/N 301818M)
Comment:

T-score vs. White Male. Source:2012 BMDCS/NHANES. Z-score vs. White Male. Source:2012 BMDCS/NHANES.

DXA Results Summary:

Scan Date	Age	BMD (g/cm²)	T - score	BMD Change (g/cm²) vs Baseline	BMD Change (g/cm²) vs Previous
10/07/2022	64	1.158	-0.4	-0.009 (-0.8%)	-0.009 (-0.8%)
08/22/2022	64	1.167	-0.3		

* Denotes significance at 95% confidence level, LSC is 0.014 g/cm²

Figure6. *DXA scan BMD change from SD to KD conditions*

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