The Acute Effects of Coffee Ingestion on Postural Control and Physical Function in Older Adults: A Randomised Crossover Trial

ABSTRACT

Caffeine consumption can elicit improvements in aspects of physical function in older adults but also, negatively modify standing balance, potentially increasing fall risk. However, balance alterations and changes in physical function induced by commonly consumed caffeine vehicles such as coffee have not been investigated. Therefore, this study investigated coffee ingestion providing 3 mg·kg BW^{-1} caffeine on balance performance and physical function, in a group of older adults. In a randomised, crossover design, 22 older adults (Male *n*=10, Age: 68±6 years) completed bipedal standing balance and physical function assessments (Senior Fitness Test) under one of the following conditions: caffeinated coffee (COF), decaffeinated coffee (DEC), placebo (PLA) or a control (CON) (no fluid ingestion). Centre of pressure (COP) root mean square and power frequency were calculated to characterise postural performance and strategy, respectively. The complexity (i.e., regularity) of the COP signal was also determined by calculating sample entropy. Caffeinated coffee had limited effects on COP outcomes. Frequency of the COP in the anteroposterior direction was greater following COF compared to DEC (P=0.047;*g*=0.29) but there were no statistical differences between COF and PLA or CON (P>0.05). Furthermore, there were no significant performance differences between any conditions in all tests of physical function (P>0.05). This suggests that coffee has limited effects on balance performance or physical function but may influence both balance complexity and the strategy utilised to maintain upright stance. Overall, a strong cup of coffee does not significantly influence balance and measures of functional performance in healthy older adults.

INTRODUCTION

Ageing is characterised by the progressive loss of muscle mass, muscle strength, and a decline in physical function (Barber et al., 2015) with these detriments being accelerated by physical inactivity (Doherty, 2003). The COVID-19 pandemic largely had a negative impact on physical activity (PA) behaviour (Stockwell et al., 2021). As a result of reduced PA, prediction modelling estimates 110,000 more older adults will have at least one fall per year incurring substantial additional costs to the National Health Service over coming years (Public Health England, 2021). Therefore, it is evident that understanding factors that may negatively influence postural control and consequently, contribute to increased fall risk in older adults would be welcome public health information.

Caffeine is a widely consumed psycho-active substance known for its ability to increase and/or maintain physical performance (McLellan et al., 2004). Caffeine's primary ergogenic mechanisms of action are considered to arise from the antagonism of adenosine receptors (specifically A1 and A2a subtypes) leading to an increase in neurotransmitter release, motor unit firing rates, pain suppression, reduced fatigue, improved neuromuscular performance (Davis & Green, 2009), heightened alertness and increased arousal (Astorino et al., 2012). Whilst work in this area specific to older adult populations is sparse, evidence indicates that acute caffeine consumption may evoke small but significant improvements in muscular strength and power (Grgic et al., 2018), improve functional performance (Duncan et al., 2014) and enhance skeletal muscle rate of force development which is implicated in better balance control (Grgic & Mikulic, 2022).

Despite evidence of caffeine consumption having many positive effects for older adults, a recent systematic review (Briggs et al., 2021) concluded that the acute ingestion of a moderate to high dose of anhydrous caffeine (200-400 mg) administered in capsule form adversely influences older adults' ability to minimise postural sway during quiet standing. As increased sway amplitude during upright stance has previously been linked to greater risk of falling (Johansson et al., 2017), careful consideration of increased fall risk with acute caffeine consumption in older adults is warranted. However, current interpretations of the literature lack practical application, as studies have failed to consider a widely consumed caffeine vehicle in older adults, *coffee* (Torres-Collado et al., 2018). Whilst coffee contains caffeine, it is also comprised of more than 1000 other compounds (Gonzalez de Mejia & Ramirez-Mares, 2014). These additional non-caffeine components (e.g. polyphenols, lipids and minerals (Nuhu, 2014) may modify the ergogenic effects of caffeine contained in coffee, either by attenuating or amplifying caffeine's effects on postural control. Indeed, an increase in alertness and tests of cognition have been highlighted with decaffeinated coffee (Haskell-Ramsay et al., 2018) as well as beneficial effects on aspects of physical function in older adults (Wang et al., 2021). Therefore, the potential synergistic interaction of caffeine and other compounds in coffee must be considered. Given that coffee represents a widely utilised caffeine ingestion vehicle, particularly amongst older adults, with 80% of the UK population buying and consuming instant coffee (British Coffee Association, 2024) there is a need to understand whether the effects of caffeinated coffee differ to the effects of anhydrous caffeine ingestion on postural control in older adults (Briggs et al., 2021).

Previous studies examining the effects of caffeine on postural control have utilised traditional linear measures (i.e. centre of pressure [COP] amplitude) to characterise balance *performance* (Jensen et al., 2011; Momsen et al., 2010; Norager et al., 2005; Swift & Tiplady, 1988; Tallis et al., 2020). As a comprehensive assessment of postural control should involve several descriptors of the COP (Schubert et al., 2012), the use of *non-linear* (e.g. sample entropy) and *frequency-based* (i.e. mean power frequency) measures provide novel insight into different balance strategies adopted during quiet standing which previous investigation has failed to consider. For example, an increase in mean power frequency (MPF) of the COP is reliably associated with increased lower limb co-contraction – an effective strategy during quiet standing to reduce postural sway (Warnica et al., 2014), but is potentially maladaptive during dynamic situations (i.e. postural perturbations) (Falk et al., 2022). Furthermore, sample entropy can be used to detect regularity of the COP time series, with low (high) values indicating more (less) regularity of postural sway dynamics (Stins et al., 2009). More specifically, changes in sample entropy may enable us to glean some of the motor control mechanisms (i.e. more/less adaptable postural control) responsible for increased postural sway with caffeine consumption. In addition to both traditional and non-linear balance measures, it is also important to examine perceptual measures of balance, such as perceived stability. For example, previous research has shown that participants who expect to perform poorly, perceive themselves to be more unstable than those who expect to perform well—irrespective of actual performance (i.e., objective postural stability) (Russell et al., 2022).

The effects of acute coffee consumption on functional performance have scarcely been investigated. Much of the positive evidence surrounding coffee has largely come from self-report measures such as the inverse association with functional disability (Wang et al., 2021). Even studies that have directly measured physical function in older adults have retrieved chronic coffee consumption information from food diaries (Jyväkorpi et al., 2021). Furthermore, a recent systematic review by Mazeaud et al. (2022) highlighted that many studies in this area have been judged to be of poor quality, but ultimately concluding that coffee does not appear to implicate poor physical functioning in older adults. Consequently, it is evident that there is a lack of controlled acute investigation into the impact of coffee on functional performance in older adults.

Therefore, this study sought to examine if coffee is detrimental to balance in older adults and whether it effects physical function, by investigating the ingestion of coffee providing 3 mg·kg body weight^{-1} of caffeine on postural control (performance and strategy) and functional performance in healthy older adults. Our hypotheses were as follows; (1) Acute ingestion of caffeinated coffee would elicit an impairment in balance performance (i.e. increased sway amplitude) that would not be present with decaffeinated coffee (DEC), placebo (PLA) or control (CON) (no fluid ingestion) (2) Caffeinated Coffee will also evoke an increase in COP frequency, reflecting more frequent postural corrections needed to maintain balance, (3) An increase in sway amplitude, reflecting a decrease in adaptability, will manifest as a reduction in variability in sway patterns (i.e. a decrease in sample entropy) (4) Caffeinated coffee will improve performance in the physical function assessments to a greater extent than all other conditions.

METHODS

Design

This was a double-blind, randomised, crossover trial with repeated measures. Condition blinding was examined using Bang's blinding index (Bang et al., 2004), where 1 represents a complete lack of blinding, 0 being consistent with perfect blinding and –1 indicating opposite guessing, which may be related to unblinding. Following ethical approval and providing informed consent, 22 older adults (Table 1) visited the laboratory at the host institute on four occasions and ingested caffeinated coffee, decaffeinated coffee, placebo or a control condition (no fluid ingestion) in a randomised order on separate occasions.

Inclusion criteria were males and females aged 60 years and over, absent of; cardiovascular disease, known cognitive impairment, uncontrolled hypertension, acute or chronic musculoskeletal injuries and no falls in the previous 6 months, all of which were assessed using a PA readiness questionnaire. All participants reported being healthy with no significant health issues. Prior to each visit, participants abstained from caffeine/ decaffeinated coffee consumption for 12 h prior to testing, as is conventional in studies of caffeine and to control for the effects of previously consumed caffeine. All testing took place at the same time of day (between 9:00am-12:00pm) to avoid circadian variation effects on performance (Jorgensen et al., 2012). For ecological validity, participant safety and comfort, participants were not required to fast before attending each trial but it was made clear not to consume any caffeine containing products and compliance was verbally checked during each visit. The CONSORT checklist for crossover trials was followed in the preparation of this manuscript with Supplementary figure 1 displaying the study flow diagram.

Power Calculation

Previous research has reported a large magnitude effect size (η^{p2}=0.32) of caffeine compared to placebo on COP outcomes in older adults (Tallis et al., 2020). Power analysis (G*Power, v3.1.9.4) showed that for a repeated measures analysis of variance (ANOVA) a minimum of 16 participants would be required to obtain 80% power (standardised medium effect size, f=0.25, α=0.05) when conducting a 4 (task) × 4 (condition) way within-subject ANOVA. Whilst previous research has reported a large effect size of placebo effects on balance performance [see Briggs et al. (2021)], we chose a more conservative effect size estimate because the low number of investigations will inherently increase the uncertainty of the true population estimate.

Table 1 about here

Pre-Assessment Measures

Prior to testing, body height (m) and mass (kg) were measured using a Seca stadiometer and weighing scales (Seca Instruments, Germany). Participants completed a self-reported questionnaire for concern about falls (16-item Falls Efficacy Scale International [FES-I]) (Yardley et al., 2005). In addition, a three-day dietary record was completed (two week days, 1 weekend day) by each participant prior to the first trial; it was then analysed (Nutritics Research Edition v5.82, Nutritics, Dublin, Ireland) to establish habitual energy, macronutrients, and caffeine consumption (Table 1). All participants then completed all tests in the order they appear below during each visit.

Postural control

Participants performed 60-s quiet standing balance tasks of progressive difficulty on a force platform (AMTI, AccuGait, Watertown, MA) (Figure 1):

(1) Eyes open firm surface (EO-FI): unaltered visual, proprioceptive, and vestibular inputs (normal condition)
(2) Eyes closed firm surface (EC-FI): removed vision, unaltered proprioceptive and vestibular inputs (proprioception dominant)
(3) Eyes open foam surface (EO-FO): modified proprioception, unaltered vision and vestibular inputs (visual dominant)
(4) Eyes closed foam surface (EC-FO): modified proprioception and vision, unaltered vestibular inputs (vestibular dominant)

Figure 1 here

The 60-s trial duration was used in accordance with previous recommendations to use at least 60-s for calculating traditional balance measures such as MPF (mean frequency in power spectrum after fast Fourier transformation) which has shown greater reliability over longer sampling durations (Carpenter et al., 2001). To ensure consistency between trials, participants stood with their feet together (Romberg stance). A foam pad (Balance-pad Plus, Alcan Airex AG, Switzerland; 50 cm in length and breadth, 6 cm in height and a density of 0.55 kg/m^3) was used for the foam task conditions. For all trials, participants were instructed to keep their hands clasped in front of the body (Johnson et al., 2023) while gazing at a black circle on a plain white wall 3 m away from the force platform. Participants rested for a minimum of 30 seconds between trials. Ground reaction force data were sampled at 100 Hz (Netforce, AMTI, Watertown, MA) and low-pass filtered offline using a fourth-order Butterworth filter with a cut off frequency of 6 Hz prior for the calculation of COP parameters. We assessed the root mean square (RMS) of the COP in the medio-lateral (ML) and antero-posterior (AP) directions (mm) as a measure of balance performance. As a comprehensive assessment of postural control should involve measures in both the time and frequency domains, we also calculated the MPF of COP data in both the ML and AP directions (Hz). These spectral properties of the COP can inform about differential postural strategies adopted during quiet standing, where a higher frequency is associated with higher stiffness around the ankle joint (Warnica et al., 2014). The MPF and RMS were derived following removal of the bias values from the signal. We also analysed the complexity (i.e., regularity) of the COP signal by calculating sample entropy (SampEn). For static balance tasks, higher values reflect more 'complex' and irregular postural adjustments.

SampEn was calculated on filtered data using a custom MATLAB script (Mathworks, United States) using the following calculations:

$$SampEn = (m, r, N) = -log\left(\frac{A}{B}\right)$$

where, m is the length of the sequences to be compared, r is the tolerance value for accepting matches, N is the length of the data, and A/B are defined as follows:

$$\boldsymbol{A} = \left\{\frac{(n-m-1)(n-m)}{2}\right\} A^{m}(r)$$

$$\boldsymbol{B} = \left\{\frac{(n-m-1)(n-m)}{2}\right\} B^{m}(r)$$

where, $A^m(r)$ is the probability that sequences match for m + 1 points, and $B^m(r)$ is the probability that sequences match for m points. We optimised the parameter settings required for the SampEn calculation, resulting in the use of m=3 and r=0.25 (Hill et al., 2024).

Immediately prior to each trial (i.e. while standing in position), participants rated how well they thought they would perform in the task (i.e "performance expectation") using a Visual Analogue Scale (VAS) from 0 ("I will not perform well at all") to 10 ("I will perform extremely well") (Russell et al., 2022). Immediately following each trial, participants were asked to rate how difficult it was to maintain balance during the task from 0 ("not difficult at all") to 10 ("maximal difficulty"). Participants were then asked to rate their degree of instability during the trial using a 0 – 10 VAS, where 0 corresponded to being "completely steady" and 10 "so unsteady that I would fall" (Castro et al., 2019).

Assessments of Physical Function

The Four-Square Step Test (FSST) was then completed in accordance with published protocols (Whitney et al., 2007). Two runs of electrical tape 180 cm in length were placed on the floor, crossing at their mid-point at an angle of 90 degrees. The squares were numbered from 1 to 4, and starting in square 1, participants rotated clockwise around the quadrants, moving into each numbered squared with both feet. This was then reversed, and participants moved around the quadrants counter-clockwise. The following instructions were given: "Try to complete the sequence as fast and as safely as possible without touching the tape. Both feet must contact the floor in each square". Participants were allowed one practice and two timed trials, with performance time measured using a stop watch. The FSST is a commonly used clinical dynamic balance assessment and has been reported to be superior to other clinical balance tools (i.e. the Timed Up and Go Test (TUG) and the Functional Reach Test) in discriminating between fallers and non-fallers (Dite & Temple, 2002). Grip-strength was then measured using a digital strain-gauge dynamometer (Takei TKK 5401, Takei Scientific Instruments, Tokyo, Japan) using instructions from the Groningen fitness test for the elderly (Lemmink et al., 2001). Finally, participants physical function was assessed using the Senior Fitness Test (SFT) (Rikli & Jones, 1999). This is an age specific functional performance battery and was performed in the following order: 30-second chair stands, arm curl performance, 8ft TUG, sit and reach and back scratch and aerobic endurance (2-minute step test).

Conditions

Each participant performed the protocol under one of the following conditions: 0.09 g·kg^{-1} coffee (COF), 0.09 g·kg^{-1} decaffeinated coffee (DEC), a placebo condition (PLA) and a control condition (CON) which consisted of no fluid ingestion. Following consumption, participants remained seated for 60 min. The Nescafé original coffee (decaffeinated and caffeinated) and placebo samples were analysed externally for their caffeine content (Laserchrom HPLC Laboratories Ltd, UK) using a High-performance liquid chromatography (HPLC) method. The coffee sample provided 35.1 mg of caffeine per 1 g of coffee meaning each participant consumed 0.09 g·kg^{-1} of coffee to achieve the 3 mg·kg^{-1} of caffeine. This dose was selected because it is ecologically valid (approximately one large strong cup of coffee), was less likely to have left participants with negative side effects (insomnia, jitters etc) and has previously shown to improve functional performance in older adults (Duncan et al., 2014) and negatively impact postural sway when administered as anhydrous caffeine (Tallis et al., 2020).

The decaffeinated coffee and the placebo contained no traces of caffeine. A PLA trial was included as the effects of the other compounds in coffee are largely unknown and so decaffeinated coffee is not a suitable placebo (Haskell-Ramsay et al., 2018). The PLA trial was hot water of the same volume and temperature as the other trials mixed with coffee flavour (Espresso Coffee Flavouring Compound, MSK Ingredients, UK) and colour (Brown Food Colouring, Lakeland, UK) to maintain treatment blinding and to ensure all trials tasted similar. All trials were dissolved in 300 ml of hot water and served in lidded cups. The CON trial allowed for any placebo effect of ingesting a warm beverage to be observed. Participants were asked to guess which trial they believed to be caffeinated coffee following all four visits.

Statistical Analysis

Data were analysed using IBM SPSS Statistics for Windows, Version 28.0 (Armonk, NY: IBM Corp.). Normality of data was assessed using the Shapiro-Wilk test and visual analysis of the plotted data to ensure the suitability of parametric tests. Two-way, repeated measures (Condition x Task) analysis of variance (ANOVA) was used to detect differences in the mean scores for all postural control measures and VAS balance scales. One-way ANOVA with repeated measures was used to examine changes in the physical function assessments. Where any differences were identified, post-hoc pairwise comparisons with Bonferroni correction were conducted. When Mauchly's test of sphericity was significant and the Greenhouse-Geisser level of violation was >0.75, degrees of freedom were corrected using Huynh-Feldt adjustment; and when violation was <0.75 Greenhouse-Geisser correction was used. Furthermore, 95% confidence intervals (95%CI) and effect sizes, partial eta squared (η_p^2), defined as trivial (<0.10), small (0.10-0.24), moderate (0.25-0.39) or large (≥0.40), and Hedges *g effect sizes*, defined as trivial (<0.20), small (0.20-0.49), moderate (0.50-0.79) or large (≥0.80) were also calculated.

Results

Bang's Blinding Index

For this calculation, the decaffeinated coffee and placebo were considered as one. The results suggest that the identification of caffeinated coffee [Mean and 95% CI: -0.35 (-0.72, 0.03)] and placebo / decaffeinated coffee [Mean and 95% CI: -0.30 (–0.69, 0.08)] were identified by random chance.

Order Effects

All data were checked for an order effect. The only test with a significant order effect was the 2-min step test ($F_{2.0,40.8}$=6.936; P<0.001; η_p^2 = 0.26) with more steps being performed on visit 2 (P=0.034; 95% CI: 0.4, 12.7; g=0.38) and visit 4 (P=0.026; 95% CI: 0.7, 15.1; g=0.47) compared to visit 1 regardless of condition.

Postural Sway Outcomes

AP-RMS

There was no significant condition x balance task interaction ($F_{5,99}$=1.285; P=0.278; η_p^2 = 0.06). There were significant differences in AP-RMS scores between conditions ($F_{3,63}$=3.305; P=0.026; η_p^2 = 0.14; Table 2) and significant differences in AP-RMS between the different balance tasks ($F_{2.2,45.5}$=232.697; P<0.001; η_p^2 = 0.92). However, pairwise comparisons revealed no significant differences between conditions and all balance tasks were significantly different from each other (P<0.05) with AP-RMS increasing with task difficulty regardless of condition.

ML-RMS

There was no significant condition x balance task interaction ($F_{4,80}$=0.976; P=0.423; η_p^2 = 0.04). There were no significant differences in ML-RMS scores between conditions ($F_{3,63}$=2.595; P=0.060; η_p^2 = 0.11; Table 2) but there were significant differences in ML-RMS between the different balance tasks ($F_{1.8,37.1}$=237.679; P<0.001; η_p^2 = 0.92). Pairwise comparison revealed significant differences between all balance tasks (P<0.001) with the exception between EO-FI and EC-FI (P=0.097; 95% CI: -1.1,0.1; g=0.37).

AP-MPF

There was no significant condition x balance task interaction ($F_{5,107}$=1.714; P=0.09; η_p^2 = 0.08). There were significant differences in AP-MPF scores between conditions ($F_{3,63}$=3.521; P=0.020; η_p^2 = 0.14; Table 2) and significant differences in AP-MPF between balance tasks ($F_{3,63}$=54.550; P<0.001; η_p^2 = 0.72). Pairwise comparisons revealed AP-MPF under COF, was significantly greater than DEC (P=0.047; 95% CI: 0.0, 0.07; g=0.29). Pairwise comparisons also revealed that AP-MPF was significantly different between all tasks (P<0.05) with AP-MPF increasing with task difficulty.

ML-MPF

There was no significant condition x balance task interaction ($F_{9,189}$=0.911; P=0.517; η_p^2 = 0.04). There were significant differences in ML-MPF scores between conditions ($F_{3,63}$=2.996; P=0.037; η_p^2 = 0.13; Table 2) and significant differences in ML-MPF between balance tasks ($F_{2.2,45.4}$=30.186; P<0.001; η_p^2 = 0.59). However, pairwise comparisons revealed no differences between conditions. Further pairwise comparisons revealed significant differences between all balance tasks (P<0.05) except between EC-FI and EO-FO (P=1.000; -0.0,0.1; g=0.01). In general, ML-MPF increased with task difficulty.

AP-SampEn

There was no significant condition x balance task interaction ($F_{5,113}$=1.323; P=0.227; η_p^2 = 0.06). There were significant differences in AP-SampEn scores between conditions ($F_{3,63}$=3.560; P=0.019; η_p^2 = 0.15; Table 2) and significant differences between balance tasks ($F_{3,63}$=13.015; P<0.001; η_p^2 = 0.38). However, pairwise comparisons revealed no significant differences between any conditions. Further post hoc testing revealed that AP-SampEn scores were significantly lower for EC-FO than

EO-FI (*P*=0.03; 95% CI:-0.14,-0.02), EC-FI (*P*<0.001; 95% CI:-0.13,-0.05) and EO-FO (*P*=0.08; 95% CI:-0.11,-0.01).

ML-SampEn

There was no significant condition x balance task interaction ($F_{9,189}$=1.233; *P*=0.277; η_p^2 = 0.06). There were significant differences in ML-SampEn scores between conditions ($F_{3,63}$=3.974; *P*=0.012; η_p^2 = 0.16; Table 2) and significant differences between balance tasks ($F_{3,63}$=59.924; *P*<0.001; η_p^2 = 0.74). Post hoc tests revealed that ML-SampEn scores were greater for COF compared to CON (*P*=0.014; 95% CI:0.01,-0.05) and scores for CON were lower than PLA (*P*=0.013; 95% CI:-0.05,-0.00). Post hoc testing for balance tasks revealed that EO-FI was not different to EC-FI, but all other comparisons were (*P*<0.001).

Subjective Balance Outcomes

Performance Expectation

There was no significant condition x balance task interaction ($F_{5,96}$=0.450; *P*=0.805; η_p^2 = 0.02). There was no significant effect of condition on perception of how well participants thought they would perform ($F_{3,60}$=0.255; *P*=0.858; η_p^2 =0.01; Table 2) but there were significant differences in perceptions of how well they would perform each balance task ($F_{2,39.6}$=47.602; *P*<0.001; η_p^2 =0.70). Pairwise comparison revealed that only the EC-FI and EO-FO conditions were not different from each other (*P*=1.000; 95% CI: -0.6, 1.0).

Perceived Instability

There was no significant condition x balance task interaction ($F_{5,94}$=1.026; *P*=0.421; η_p^2 = 0.05). There was no significant effect of condition on perceived instability ($F_{3,60}$=1.207; *P*=0.315; η_p^2 = 0.06; Table 2) but there were significant differences between balance tasks ($F_{1.8,36.2}$=42.891; *P*<0.001; η_p^2 = 0.68). Pairwise comparisons revealed that in general, instability increased with task difficulty (*P*<0.001) with only EO-FI and EC-FI not being significantly different from each other (*P*=0.177; 95% CI: -1.3, 0.1).

Perceived Task Difficulty

There was no significant condition x balance task interaction ($F_{4,86}$=0.735; *P*=0.579; η_p^2 = 0.04). There was no significant effect of condition on perceived task difficulty ($F_{3,60}$=0.525; *P*=0.667; η_p^2 = 0.03; Table 2) but there were significant differences between balance tasks ($F_{2,39.6}$=55.922; *P*<0.001; η_p^2=0.74). Perceived task difficultly increased with the difficulty of each task with pairwise comparisons revealing significant differences between all balance tasks (*P*<0.001).

Table 2 here

Physical Function Assessments

There was no significant effect of condition on time to complete the FSST (F3,60=2.365; *P*=0.080; η_p^2 = 0.11), repetitions performed in chair sit to stands (F3,60=0.600; *P*=0.618; η_p^2 = 0.03), completed arm curl repetitions (F2,40.9=1.680; *P*=0.181; ηp2 = 0.08), grip strength (F3,60=0.429; *P*=0.733; η_p^2 = 0.02), or right (F3,60=0.459; *P*=0.712; η_p^2 = 0.02) and left (F3,60=1.093; *P*=0.359; ηp2 = 0.05) leg flexibility (Table 3). There was no significant effect of condition on right ($F_{3,60}$=0.973; *P*=0.412; η_p^2 = 0.05; Table 3) and left ($F_{3,60}$=0.459; *P*=0.712; η_p^2 = 0.02; Table 3) arm flexibility or 8FT TUG performance ($F_{3,60}$=2.123; *P*=0.107; η_p^2 = 0.10; Table 3). Finally, there was no significant effect of condition on number of steps completed ($F_{3,60}$=0.838; *P*=0.479; η_p^2 = 0.04; Table 3).

Table 3 here

Discussion

This is the first study to evaluate balance performance and physical function performance following the ecologically valid aministration of caffeine via coffee in older adults. Bang's blinding index suggest that older adults in the present study were successfully blinded to the identity of conditions. Contrary to our first hypothesis, we did not observe any effects of coffee ingestion on the amplitude of postural sway meaning we must reject this hypothesis. The lack of coffee-derived adverse effects on balance *performance* observed in the current study is in broad disagreement with the literature on caffeine (Jensen et al., 2011; Momsen et al., 2010; Norager et al., 2005; Swift & Tiplady, 1988; Tallis et al., 2020). To provide insight into the effect of caffeine on postural control *strategy*, we also calculated the frequency (MPF) and complexity (SampEn) of the COP. Caffeinated coffee elicited an increase in the MPF (indicative of a postural “stiffening” strategy) and the SampEn, which could reflect a more adaptable postural control system. Furthermore, we observed no changes in functional performance measures or perceptual balance measures in the COF condition compared to all other conditions. Collectively, our findings expand upon the existing research utilising anhydrous caffeine ingestion on postural control, providing evidence that the acute ingestion of caffeinated coffee consumption has limited effects on balance performance, but may influence both balance complexity and the strategy utilised to maintain upright stance. In this regard, this study offers important insights into the safety of coffee consumption not only for its effects on balance performance, but also novel insight into the underlying balance control strategies that are adopted.

It is important to highlight that whilst some COP outcomes were different during COF, these differences were not significant between all conditions meaning hypothesis two is only partially supported. Consequently, our collective findings imply that acute ingestion of caffeinated coffee is unlikely to be a significant acute risk factor for impaired balance performance among older adults. Our findings suggest that older adults can select any of the hot beverages used in this study without any immediate consequences to their ability for postural control or their functional performance and importantly no consequences to their perception of balance performance, perceived instability, or perceived difficulty of balance tasks.

One possible explanation for our difference in findings compared to the caffeine literature may be that the non-caffeine compounds in coffee nullify some of the negative consequences of caffeine (i.e., anxiety, jitters, increased ventilation etc.) on postural control mechanisms. Furthermore, caffeine’s effects on postural control may be dose dependent. Ben Waer et al. (2021) observed that low caffeine doses (100 mg) elicited a more positive effect on balance control than higher caffeine doses (400 mg). Thus, the moderate absolute caffeine doses utilised in the present study (3 $mg \cdot kg^{-1}$; 131-286mg) may have not been high enough to elicit measurable disruptions in postural control in this cohort of older adults. However, previous research utilising the same caffeine dose (3 $mg \cdot kg^{-1}$) in anhydrous form has reported increases in postural sway in older adults (Tallis et al., 2020). This further highlights the need for researchers to understand the synergistic relationship between various non-caffeine components of coffee that may be influencing performance. Furthermore, differences in postural sway outcome measures between studies may explain contradictory findings. Although the outcome measures used in the present study provide appropriate assessment of balance *performance*, they may not be directly associated to COP outcome measures used in previous work (Briggs et al., 2021). Furthermore, caffeine typically elicits small but significant effects that can be difficult to detect through a host of other confounding factors (Tamilio et al., 2022) which may help explain the null findings observed in the present study.

Despite the limited effects of coffee consumption on postural control observed in the present study, one notable and novel finding was that sway frequency was greater during COF compared to DEC. An increase in sway frequency typically reflects a postural behaviour often associated with increased ankle muscle co-contraction (i.e., increased ankle stiffness), presumably an attempt to provide more joint stability and maintain a tighter control of the centre of mass within the boundaries of the base of support (Warnica et al., 2014). However, when combined with the (unaltered) sway amplitude responses, these findings imply that the increased co-contraction did not lead to functional improvements in postural control. In this context, the increased sway frequency during COF appears maladaptive (Nagai et al., 2011; Warnica et al., 2014). One interpretation for the tendency of an increase in frequency with unaltered amplitude during COF is that of a failed attempt from the central nervous system to freeze the degrees of freedom in the postural chain (i.e., ‘tighter’ postural control).

Furthermore, COP complexity (SampEn) was greater during COF compared to CON. A less regular COP pattern (an increase in sample entropy) is thought to reflect a shift toward less attention needed to maintain balance (Roerdink et al., 2011) and thus a more *automatic* and *adaptable* control of body sway (Donker et al., 2007) meaning hypothesis three is plausible. Furthermore, COP complexity during CON was lower than PLA which may be explained by a caffeine expectancy effect. When standing on foam compared to a firm support surface, the more challenging task conditions are thought to require a higher degree of attentional involvement in balance (Franco et al., 2018). Thus, our interpretation of the present findings is that the higher COP complexity, coupled with the increased MPF, observed during COF could be attributed to a reduction in cognitive resources needed to maintain balance, potentially pointing towards the use of a more automatic balance control strategy (Roerdink et al., 2011). Greater automaticity of balance control is functional as it may allow for concurrent performance and control of attention-demanding tasks, like planning to navigate around moving people/obstacles (Richer & Lajoie, 2020). However, the overall practical importance of the increased complexity and frequency of COP adjustments is questionable considering the lack of statistical difference between COF with PLA and DEC.

Lastly, in contrast with caffeine research (Duncan et al., 2014) there were no changes in performance in any of the physical function assessments meaning we reject hypothesis four. There were also no changes in the four-square step test in COF which also differs to findings in caffeine research (Tallis et al., 2020). Therefore, in the present study, as the effects on standing balance were congruent with the functional tasks that also assess facets of dynamic balance performance (e.g., FSST and TUG) it increases confidence that coffee ingestion has had limited effects on balance performance in older adults.

When considering the limitations of the present study, it is important to note that the older adults that took part were already active and at or above the age expected norm values suggested by Rikli and Jones (1999). Therefore, any effects of caffeinated coffee may have been masked by adequate functional status in the balance tasks and by a ‘ceiling effect’ in the sensitivity of performance measures in the SFT. Furthermore, given that COF showed only small differences to other conditions, it is difficult to attribute any observed effects with confidence. Consequently, the generalisability and robustness of the changes in COP frequency and complexity with COF may be compromised. We urge readers to exercise caution when extrapolating the results to broader contexts or making practical recommendations based on these findings.

Finally, future studies would benefit from examining the effects of coffee on less active and functionally capable older adults e.g., in those with impaired balance. Investigating coffees’ effects at higher dosages of caffeine than used in the present study is needed and examining the acute effects of isolated coffee constituents (e.g. chlorogenic acids and polyphenols) on postural control and balance performance would be valuable next steps.

Conclusion

The present study represents the first investigation of balance performance responses to acute coffee ingestion in older adults. We observed that caffeinated coffee at a dose of 3 mg·kg^{-1} caffeine does not adversely influence balance performance in older adults. We additionally found that acute coffee ingestion may influence the complexity and frequency of COP adjustments, behaviours that are associated with shifts in attention and postural control strategy, respectively. These observations expand upon existing research in older adults, providing important new insight into the effects of acute coffee ingestion on balance performance and strategies in older adults. Furthermore, there was no impact on performance in any of the physical function assessments under any condition in this study suggesting that both coffee and decaffeinated coffee do not acutely alter balance or performance in tests of physical function. We contend that healthy older adults that consume a strong cup of coffee are unlikely to cause impairments or improvements to functional and balance performance.

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Conflict of interest

The authors declare no conflicts of interest.

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