

RESEARCH ARTICLE OPEN ACCESS

Stress-Induced Responses in Conscious Movement Processing and Walking Behaviour in Older Adults

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Received: 16 October 2024 | **Revised:** 2 June 2025 | **Accepted:** 5 June 2025

Funding: This study was supported by Research Grants Council, University Grants Committee.

Keywords: conscious movement processing | environmental stressor | older adults | walking behaviour

ABSTRACT

We investigated how psychological and walking behaviours would respond to environmental stressor between older adults with different psychomotor tendencies. We recruited 102 community-dwelling older adults and split them into those with higher conscious movement processing tendencies (HCMP) and lower conscious movement processing tendencies (LCMP). Participants walked straight for 7.4 m in a normal environment (level-ground surface) and in a challenging environment (elevated, foam surface). Real-time conscious movement processing (indicated by T3-Fz electroencephalography coherence), walking stability (indicated by the variabilities in gait parameters and medial-lateral excursion of upper body sway), and neuromuscular efficiency (indicated by co-contraction index of lower limb muscles) were assessed. When older individuals were walking under a challenging environment, LCMP significantly increased their real-time conscious movement processing, while HCMP maintained at a consistent level compared to walking on a normal environment. Both groups significantly reduced walking stability and efficiency to the same extent under the challenging environment. LCMP appear to be susceptible to exhibiting environmentally induced conscious movement processing accompanied by less stable and efficient walking behaviour; indicating the need to investigate this cohort who are often assumed to have lower fall risk. HCMP responses seem independent of environmental stressor as a further increase in conscious involvement might be limited by overloaded working memory, leaving less capacity for adapting to additional stressors. Future research should target older adults at a higher risk of falling, as the negative impact of elevated conscious movement processing could be more pronounced in the absence of compensatory adaptations from higher physical function.

Clinical Trial Registration: The trial was pre-registered in the [ClinicalTrials.gov](https://clinicaltrials.gov) (ID: NCT05411536) prior to data collection.

1 | Introduction

Walking is a motor skill learnt and adapted gradually with automaticity as we overcome various developmental milestones (Adolph and Robinson 2013). Yet, it is also one of the most common fall-related activities among the older population (Li et al. 2006), which can be attributed to various factors as we age. One potential psychological mechanism underlying falls in older adults could be heightened conscious

processing of an automatic movement (e.g., walking). Conscious movement processing refers to the intentional contemplation of a movement or motor skill in progress (a state) in an attempt to enhance movement efficiency (R. Masters and Maxwell 2008). However, the excessive increase in conscious processing of an automatic movement can shift motor control from an automatic mode to a conscious one (R. S. W. Masters et al. 1993). This shift involves consciously executing a movement by directing their attention

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internally with the use of explicit procedural knowledge of the skill performed (R. Masters and Maxwell 2008). Therefore, when faced with stressful situations like movement difficulties, increased fear of falling or treacherous environments, older adults may exert greater conscious processing over their walking.

However, this increased conscious regulation can disrupt movement automaticity and compromise walking behaviour, potentially elevating their risk of falling (Uiga et al. 2020). For instance, previous research has reported both reduced postural stability and increased gait variability—indicative of hampered walking stability—during experimentally induced conditions of conscious movement processing in older adults (Mak, Young, Chan, et al. 2020). Similarly, Mak et al. (2019) observed reduced neuromuscular efficiency—represented by increased muscle co-contraction—when older adults with a history of falls consciously processed their body movements. These consequences likely result from the disruption of subconscious (automatic) systems that normally regulate highly coordinated, complex motor skills, such as postural control and locomotion (R. Masters and Maxwell 2008). While walking stability and neuromuscular efficiency are directly related to fall risk in older adults, examining how conscious movement processing affects these outcomes can better understand factors that contribute to falls. Moreover, older adults frequently experience a reduction in cognitive resources, which can impede their ability to manage multiple tasks concurrently (Schaefer and Schumacher 2011). Engaging in conscious movement processing, particularly under stress, can deplete these limited cognitive resources, thereby reducing the capacity available for essential tasks such as maintaining balance and responding to environmental changes (Ellmers and Young 2018). This heightened cognitive load may increase the risk of falls, as it compromises the ability to swiftly and effectively adapt to unforeseen circumstances (Schaefer et al. 2015).

Since the excessive increase in conscious movement processing appears unfavourable, a tool to assess older adults' propensity for this psychological response may help identify those who would benefit most from targeted interventions. The Movement Specific Reinvestment Scale (MSRS) or its Chinese version (MSRS-C) is used to assess an individual's predisposition (a trait) to reinvest cognitive resources into their movements (R. S. W. Masters et al. 1993, 2005); equivalent to trait conscious movement processing. Wong et al. (2008) demonstrated that older adults with a history of falls have a higher trait conscious movement processing than those without a history of falls. This finding suggests that older adults with a higher tendency to consciously process their movements may be more susceptible to falls. However, subsequent studies by Mak et al. (2021) and Mak et al. (2020) have examined the impact of trait conscious movement processing on walking patterns in older adults and indicated no significant association between the two. This is possibly due to their level-ground walking tasks not sufficiently stressful enough to stimulate outcome changes (Mak, Young, Chan, et al. 2020). It has also been argued that the MSRS-C, as a trait measure, might not be sensitive enough to detect changes in real-time conscious movement processing among healthy older adults (Mak et al. 2021; Mak and Wong 2022).

To better understand the mechanisms of conscious movement processing in relation to walking behaviour, this study aims to extend previous investigations by Mak et al. (2019) and Mak, Young, Chan, et al. (2020) through combining two novel methodological approaches: (1) electroencephalography (EEG)-derived measures of conscious movement processing during walking and (2) the utilisation of a more challenging walking surface designed to induce stress. We aim to capture how conscious movement processing disrupts automatic motor control that contributes to (1) inconsistent gait patterns (indicated by increased variability, excessive body sway) and (2) inefficient neuromuscular recruitment that constrains the motor system (indicated by heightened muscle co-contractions) (R. Masters and Maxwell 2008; Wulf et al. 2001). To address the limitation of previous studies, we examined real-time conscious movement processing at baseline and avoided relying on trait measure, which may be insensitive to real-time changes and their effects on walking behaviour under increased stress. The use of EEG T3-Fz coherence, which assesses the linear association in the spectral domain between the signals from the left temporal region (associated with verbal-analytical processing) (Hauffer et al. 2000) and the frontal midline region of the cortex (associated with motor planning) (Kaufler and Lewis 1999), has been suggested as an objective method to indicate the real-time involvement of conscious processing during a motor task (Chan et al. 2019; Chow et al. 2019; Zhu et al. 2011). Moreover, unlike previous investigations which adopted a level-ground walkway, this study utilised a novel experimental manipulation: an elevated, foam walking surface. The biomechanical properties of foam (e.g., compressibility, reduced proprioceptive feedback) are well-documented to induce postural instability (Lord and Menz 2000; Wright and Laing 2011). Therefore, testing on an unstable foam surface may simulate a stressful environment by potentially inducing physiological stress responses, such as increased heart rate and respiratory frequency, due to the heightened postural threat and perceived risk of falling (Carpenter et al. 2006; Farias et al. 2023).

Our main objective was to examine the psychological (i.e., levels of real-time conscious movement processing) and behavioural changes (i.e., walking stability and neuromuscular efficiency) in older adults with different baseline conscious movement processing tendencies under a novel, foam-surface walking task. Given that older adults with a higher conscious movement processing tendency (HCMP) are often considered to allocate more cognitive effort in processing movement mechanics during walking (Uiga et al. 2015), we hypothesised that when asked to walk on a challenging environment, HCMP would exhibit a greater increase in real-time conscious movement processing than those with a lower conscious movement processing tendency (LCMP). In addition, HCMP who rely heavily on conscious processing for walking may have limited capacity to allocate additional resources to adapt to the increased cognitive demands from stress (Woollacott and Shumway-Cook 2002). As a result of the interplay between cognitive overload and heightened conscious movement processing, we expect that they would exhibit a greater decline in walking stability (represented by increased gait variability and medial-lateral (M-L) body sway) than LCMP. While variability can indicate adaptability in some contexts, heightened variability in older adults on unstable surfaces might reflect less effective compensation for instability

(Gabell and Nayak 1984; Thies et al. 2005). We also expect that HCMP would exhibit a greater decline in neuromuscular efficiency (represented by increased muscle co-contraction) than LCMP as the process of heightened conscious movement processing might unintentionally re-freeze various neuromuscular degrees of freedom, resulting in inefficient motor recruitment and disrupted automaticity of movement (R. Masters and Maxwell 2008; Wulf et al. 2001). While heightened conscious movement processing tendency has been implicated to falls in older adults (Wong et al. 2008), further understanding the psychological mechanism in relation to stress is crucial for informing the development of psychomotor gait training in fall rehabilitation, which aims at mitigating the effects of heightened conscious movement processing and reducing fall risks in older adults when facing challenging walking environments in the community.

2 | Methods

2.1 | Participants

One hundred and six community-dwelling healthy older adults were recruited by convenience sampling from local community centres. A previous study reported an effect size of 0.61 for the difference in real-time conscious movement processing between a level-ground walking task and a foam walking task (Mak et al. 2021). The sample size calculation (effect size = 0.61, $\alpha = 0.05$, power = 0.8) with an additional 20% dropouts suggested a total sample size of approximately 106 participants to provide adequate power for the study. All participants must be: (1) aged 65 or above; and (2) able to walk independently indoors for at least 20 m without a walking aid. They were excluded if: (1) the total score of the Chinese version of the Mini-Mental State Examination (MMSE-C) was less than 24 (Chiu et al. 1994); (2) they had any untreated cerebral vascular disease, Parkinson's disease, or any other neurological deficit present; (3) they had any unstable medical condition present affecting safety while walking; (4) there was a history of a major fall incident within the last year; or (5) the total score of static visual acuity was poorer than 20/40 (assessed using the Tumbling E eye chart). Informed consent was obtained from all participants prior to any experimental procedures.

2.2 | Procedures

Before the walking trials, a series of structured questionnaires collected participants' demographics (i.e., age, gender, medical, fall history, social and socioeconomic information) and other baseline psychological measures. Fear of falling was assessed using the Chinese version of the Falls Efficacy Scale International (FES-I (Ch)) (Kwan et al. 2013), with higher scores representing a greater concern about falling. Trait conscious movement processing was examined using the Chinese version of the Movement Specific Reinvestment Scale (MSRS-C), with higher scores indicating a higher trait conscious movement processing. Baseline physical measures, including the Berg Balance Scale (BBS) and the Timed Up and Go Test (TUG), were assessed to evaluate functional balance ability and functional

mobility, respectively (Berg et al. 1989; Shumway-Cook et al. 2000). A higher BBS score indicates a lower risk of falling, while a completion time greater than 14s in TUG indicates a higher risk of falling (Shumway-Cook et al. 2000).

After collecting clinical baseline measurements, the walking task required participants to complete a series of walking trials at a natural and self-selected pace along a 7.4 m walkway on a level-ground surface and an elevated, foam surface, respectively. The dimensions of the foam walkway were 8 m (length) x 0.8 m (width) x 0.3 m (height). The foam walkway's starting and ending points were positioned on the foam surface, requiring participants to step onto the foam before beginning each trial. The starting and finishing markers of the foam walking trials were positioned at 0.3 m from each side of the foam edges. This is equivalent to a total walking length of 7.4 m for both walking surfaces. This walking path was of similar length as previous research to sufficiently determine the associations between variability of gait parameters and falls in older populations (Brach et al. 2005). Participants stepped off the foam before executing any turning motion, which was therefore not included in the analysis. To account for gait initiation and termination, we excluded the first and last meter from the 7.4-m walking length of the walkways in our analysis.

2.3 | Walking Trials

All walking trials on the level-ground surface were performed before the walking trials on the foam surface. Each participant performed one practice trial along the level-ground and foam walkway, respectively, to familiarise themselves with the laboratory environment before the start of each walkway. Three walking trials were subsequently performed under each walkway respectively after the practice trial, equivalent to a total of six walking trials without specific instructions. For every walking trial, regardless of condition, participants were only given general instructions, "Please use your natural, comfortable walking pace to complete the walkway. You can start walking now" at the beginning.

All main outcomes were measured under walking trials on both surfaces. In particular, the real-time conscious movement processing measured under the level-ground surface, rather than the MSRS-C scores, was also utilised as the baseline measure to represent the conscious movement processing tendency of older adults in this study, as it is believed to be more truly reflective to the change in real-time conscious movement processing under the foam surface (Mak et al. 2021; Mak and Wong 2022).

2.4 | Apparatus

2.4.1 | Primary Outcome Measure

Alpha 2 Electroencephalography (EEG) coherence between T3 (verbal-analytical region) and Fz (motor planning region) (i.e., T3-Fz EEG coherence) was collected to detect the primary outcome of real-time conscious movement processing during all six walking trials (Ellmers et al. 2016; Zhu et al. 2011). The

T3-Fz EEG coherence indicates the utilisation of verbal knowledge in conscious movement control as a reflection of the real-time conscious movement processing (Zhu et al. 2011). According to the standard international ten-20 electrode system (Klem et al. 1999), T3, T4 (visuospatial region), and Fz electrodes were placed on the left and right temporal region and frontal midline, respectively. The ground, reference, and an additional electrode (eye blink) were then placed on the right mastoid, left mastoid, and left zygomatic bone correspondingly (Zhu et al. 2011). The real-time EEG activity was measured using a wireless EEG device with a sampling frequency of 200 Hz (Brainquiry PET 4.0, Brainquiry, The Netherlands). It was recorded by biophysical data acquisition software (Bio-Explorer 1.5, CyberEvolution, US). The average Alpha 2 T3-Fz EEG coherence for each walking condition was calculated based on the respective three walking trials per participant in a biophysical data processing and analysis software (BioReviewer 1.5, CyberEvolution, US) (Zhu et al. 2011). The EEG data were processed using previously established algorithms (Zhu et al. 2011). The raw EEG signals were filtered through a low pass filter (42 Hz) and a high pass filter (2 Hz) to remove potential biological artefacts and noise. Prior to each measurement, an impedance test was conducted using a 48–52 Hz filter with threshold set at 20 μ V. The coherence value was computed as the squared modulus of the cross-spectrum normalised by the product of the two auto-spectra for a frequency domain, with values varying between 0 (no coherence) and 1 (highly correlated) (1-s time window, 1 Hz frequency resolution) (Carter 1987; Zhu et al. 2011). A higher T3-Fz EEG coherence indicates a greater real-time conscious movement processing. T4-Fz EEG coherence, an indication of visuo-spatial processing, was also measured to ensure any increase in T3-Fz EEG coherence is not due to the global cortical activation (Zhu et al. 2011).

2.4.2 | Secondary Outcome Measures

A three-dimensional motion-capture system (Vicon; Oxford Metrics Ltd., Oxford, UK) was utilised to measure different gait parameters, reflecting one of the secondary outcomes of walking stability (represented by gait variability and M-L body sway) during all trials. Nineteen reflective markers, captured by 16 cameras at 100 Hz, were attached to specific anatomical landmarks (e.g., pelvis, lower limbs, and feet) following the marker placements described in Mak, Young, Chan, et al. (2020) and Mak, Young, Chan, et al. (2020). The locations and movements of the markers were recorded throughout the walking trials and processed through a customised processing programme written in the MATLAB (R2015b; MathWorks Inc., USA). Marker position data were filtered with a low-pass third order Butterworth filter at 20 Hz. Heel contact was determined from the local vertical minimum of the heel marker. Toe off was defined as the significant departure from local vertical minimum of the toe marker. A stride was defined as heel-to-heel contact of the same foot. Temporal and spatial gait parameters (i.e., stride time, double support time, stance time, swing time, stride length, step length, and step width) were computed. Stride time was defined as the interval between two consecutive heel strikes of the same foot. Double support time was defined as the interval during

which both feet were on the ground simultaneously. Stance time was defined as the interval from heel strike to toe off of the same foot. Swing time was defined as the interval from toe off to heel strike of the same foot. Stride length was defined as anterior–posterior (A-P) distance between two consecutive heel strike positions of the same foot. Step length was defined as A-P distance between two consecutive heel strike positions of the opposite feet. Step width was defined as M-L distance between two consecutive heel strike positions of the opposite feet. The variability of gait parameters was represented by the standard deviation (SD) of respective gait parameters, while the M-L excursion of upper body sway was indicated by the ranges of excursion of respective markers attached to distinct body regions. A greater variability in gait parameters and greater M-L excursion of upper body sway indicate poorer walking stability.

Surface electromyography (EMG) with a wireless telemetric system at 3 kHz (Delsys Trigno, Delsys Inc., USA) was utilised to measure the other secondary outcome of neuromuscular efficiency in all walking trials. Relevant muscle groups on each leg of the lower limbs (i.e. rectus femoris [RF], biceps femoris [BF], tibialis anterior [TA], medial gastrocnemius [MG]) were attached with EMG electrodes to measure the muscle activity (Trigno Avanti sensors, Delsys Inc., USA) according to the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) guidelines (Hermens et al. 2000). Before the start of the walking trials, maximal voluntary isometric contractions (MVICs) of the targeted lower limb muscles (TA, MG, BF and RF) were recorded by the EMG according to the protocol described by Hsu et al. (2006) for normalisation of EMG signals acquired during the walking trials. Data collected during MVIC and walking trials were filtered using a 20–500 Hz bandpass filter, full-wave rectified and smoothed with the root mean square (RMS) algorithm with a 100 ms window. The peak value for MVIC was averaged over a 500 ms window, and was used to normalise the amplitude of EMG signals of the respective muscles collected from the walking trials. The normalised EMG signals were used to obtain the co-contraction index (CCI) of lower limbs (Frost et al. 2002; Mak et al. 2019), which was computed by selecting the overlapping area of the normalised EMG signals for RF and BF (thigh) and TA and MG (shank) while dividing it by the total number of data points. All calculations were conducted through a customised processing programme written in the MATLAB (R2015b, MathWorks Inc., USA). A higher CCI indicates poorer neuromuscular efficiency.

2.5 | Data Analysis

Participants were divided into two groups: those with high conscious movement processing tendency (HCMP) ($n = 34$) and low conscious movement processing tendency (LCMP) ($n = 34$), by tertile split of the real-time conscious movement processing measured during walking on the level-ground surface (i.e., average T3-Fz EEG coherence of the three trials on level-ground surface). Thirty-four participants were excluded from group allocation. The raw data of T3-Fz and T4-Fz EEG coherences for three participants were missing in addition to one dropout without adverse events, and therefore not included in our analyses. We have adopted this grouping method as the median

split of the MSRS-C (trait measurement) was found to be not sensitive enough to differentiate HCMP and LCMP during a walking task (Mak et al. 2021; Mak and Wong 2022).

Statistical analysis employed IBM SPSS Statistics version 28.0 (IBM Corp, Armonk, NY, USA). A series of independent *t*-tests were conducted to compare the demographic data and the baseline measurements between HCMP and LCMP. Descriptive statistics presented both continuous (mean and standard deviations) and categorical (numbers with percentages) variables.

A series of two x 2 Group (HCMP, LCMP) x Task (level-ground surface, foam surface) mixed analysis of variance (ANOVA) with Bonferroni adjusted post hoc tests were used to investigate the interaction effects (Group x Task), between-group differences, and within-group differences in the main outcomes of real-time conscious movement processing, walking stability, and neuromuscular efficiency. The significance level was set at $p < 0.05$.

3 | Results

3.1 | Participants' Characteristics at Baseline

The baseline characteristics of age, BBS, TUG, and FES-I scores showed no significant differences between HCMP and LCMP (all $p > 0.05$) (Table 1). The mean age was 70.9 years (SD = 4.49). The majority were females ($n = 51$, 75%), and around one-half had a history of falls ($n = 33$, 48.53%). Due to technical issues of the EEG equipment leading to data loss, two participants from LCMP and five participants from HCMP were excluded from the analysis.

3.2 | Real-Time Conscious Movement Processing

3.2.1 | T3-Fz EEG Coherence

There was a significant Group x Task interaction effect on T3-Fz EEG coherence ($F[1, 59] = 14.46$, $p < 0.001$, $\eta_p^2 = 0.197$). Post hoc comparisons revealed that only LCMP showed a

significant increase in T3-Fz coherence under foam surface compared to level-ground surface ($t[32] = -4.60$, $p < 0.001$). Between-group differences were significant, as HCMP demonstrated significantly higher T3-Fz EEG coherence than LCMP under both walking surfaces (all $p < 0.001$). Figure 1 illustrates the significant interaction effect from level-ground surface to foam surface in real-time conscious movement processing.

3.2.2 | T4-Fz EEG Coherence

There was no significant Group x Task interaction ($F[1, 59] = 14.46$, $p = 0.053$, $\eta_p^2 = 0.06$) or task ($F[1, 59] = 0.63$, $p = 0.429$, $\eta_p^2 = 0.01$) effect on T4-Fz EEG coherence. HCMP demonstrated significantly higher T4-Fz EEG coherence than LCMP under both walking surfaces (all $p < 0.001$).

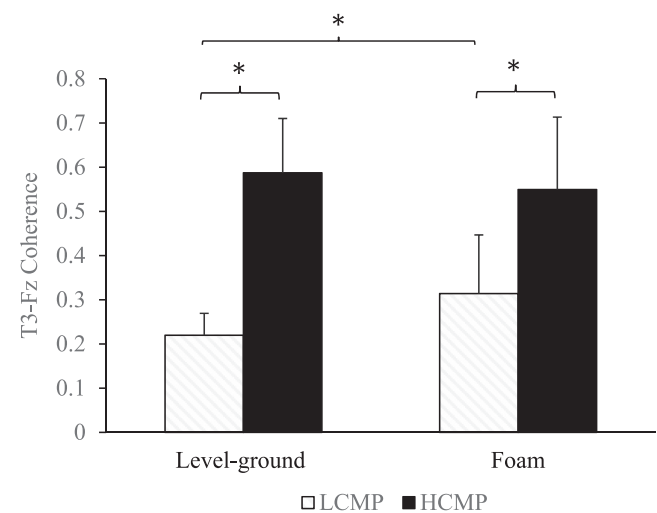


FIGURE 1 | Comparison of real-time conscious movement processing (T3-Fz EEG coherence) between LCMP and HCMP when walking in level-ground and foam surfaces. HCMP = Older individuals with high conscious movement processing tendency; LCMP = Older individuals with low conscious movement processing tendency. * $p < 0.05$.

TABLE 1 | Participants' characteristics at baseline.

Variables	Mean (SD)			<i>p</i> -value
	Total (<i>n</i> = 68)	LCMP (<i>n</i> = 34)	HCMP (<i>n</i> = 34)	
Age	70.90 (4.49)	69.91 (4.69)	71.88 (4.13)	0.07
Sex, female, <i>n</i> (%)	51 (75.00%)	26 (76.47%)	25 (73.53%)	0.78
With a history of falls, <i>n</i> (%)	33 (48.53%)	14 (41.18%)	19 (55.88%)	0.23
MSRS-C (range: 0-60)	32.57 (11.27)	33.35 (11.53)	31.79 (11.12)	0.57
FES-I (Ch) (range: 16-64)	36.51 (12.35)	36.59 (12.08)	36.44 (12.80)	0.96
TUG (seconds)	10.45 (2.32)	10.32 (2.31)	10.58 (2.35)	0.64
BBS (range: 0-56)	52.38 (2.43)	52.50 (2.65)	52.26 (2.22)	0.69
T3-Fz EEG coherence (baseline)	0.39 (0.13)	0.23 (0.05)	0.59 (0.12)	< 0.001*

Abbreviations: BBS = Berg Balance Scale; FES-I (Ch) = Falls Efficacy Scale—International (Chinese version); HCMP = Older individuals with high conscious movement processing tendency; LCMP = Older individuals with low conscious movement processing tendency; MSRS-C = Movement-Specific Reinvestment Scale (Chinese version); TUG = Timed Up and Go Test.

* $p < 0.05$.

3.3 | Walking Stability

No significant Group $\times$ Task interaction or between-group effects were found for M-L excursion of upper body sway in all regions and variability of gait characteristics (all $p > 0.05$). Significant main effects of task were observed for M-L excursion of upper body sway in all regions (Ranges of excursion of Sternum: $F[1, 59] = 39.42, p < 0.001, \eta_p^2 = 0.40$; Shoulder: $F[1, 59] = 12.65, p < 0.001, \eta_p^2 = 0.18$; Pelvis: $F[1, 59] = 29.41, p < 0.001, \eta_p^2 = 0.33$), variability of spatial gait parameters (SD of Stride length: $F[1, 59] = 29.84, p < 0.001, \eta_p^2 = 0.34$; Step length: $F[1, 59] = 108.98, p < 0.001, \eta_p^2 = 0.65$; Step width: $F[1, 59] = 35.19, p < 0.001, \eta_p^2 = 0.37$) (Figure 2), and variability of temporal gait parameters (SD of Stride time: $F[1, 59] = 186.48, p < 0.001, \eta_p^2 = 0.76$; Double-support-time: $F[1, 59] = 95.55, p < 0.001, \eta_p^2 = 0.62$; Stance time: $F[1, 59] = 176.21, p < 0.001, \eta_p^2 = 0.75$; Swing time: $F[1, 59] = 243.83, p < 0.001, \eta_p^2 = 0.81$). The variability of these outcomes significantly increased under foam surface compared to level-ground surface for both HCMP and LCMP. The mean values of spatial and temporal gait parameters are presented in Supporting Information S1: Table 1.

3.4 | Neuromuscular Efficiency

No significant Group $\times$ Time interaction or between-group effects were found for CCI of thigh and shank (all $p > 0.05$). Significant main effect of task was observed only for CCI of thigh ($F[1, 59] = 6.63, p = 0.013, \eta_p^2 = 0.10$) (Figure 3), as it significantly increased under foam surface compared to level-ground surface for both HCMP and LCMP. HCMP had a significantly lower CCI of thigh than LCMP under level-ground surface ($p < 0.001$) and foam surface ($p = 0.016$).

4 | Discussion

This study examined the changes in psychological and walking behaviours in older adults with different conscious movement processing tendencies when introduced to a challenging walking environment.

No significant change in real-time conscious movement processing was observed between normal and challenging environments in HCMP. Although HCMP exhibited higher T3-Fz EEG coherence than LCMP when walking on an elevated, foam surface, this only partially supported our hypothesis, as it

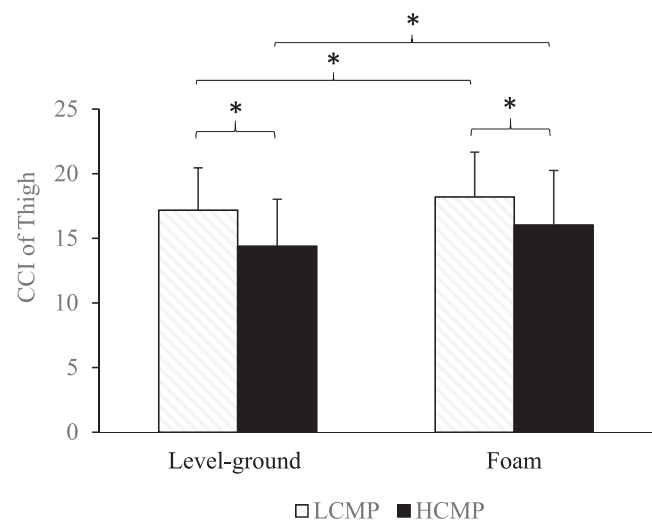


FIGURE 3 | Comparison of neuromuscular efficiency (CCI of thigh) between LCMP and HCMP when walking in level-ground and foam surfaces. CCI = Co-contraction Index; HCMP = Older individuals with high conscious movement processing tendency; LCMP = Older individuals with low conscious movement processing tendency. * $p < 0.05$.

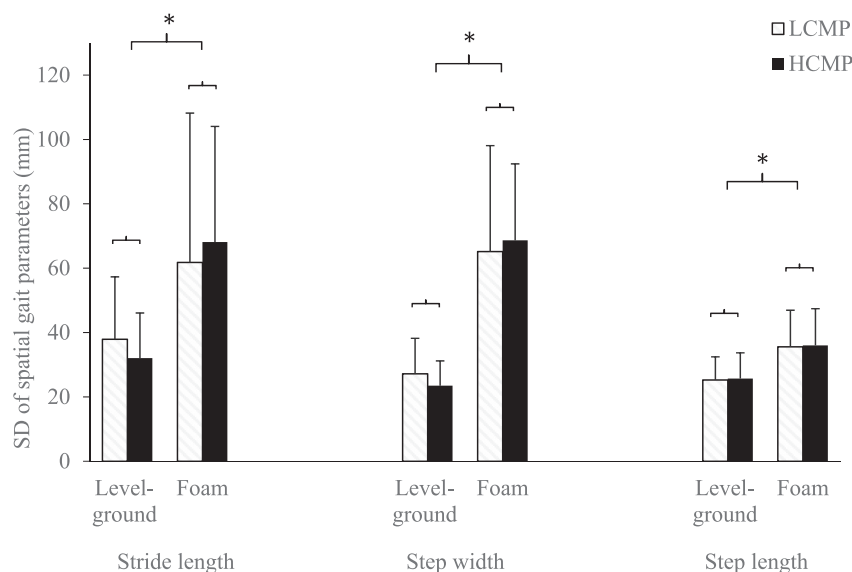


FIGURE 2 | Comparison of variabilities (SD) in spatial gait parameters between LCMP and HCMP when walking in level-ground and foam surfaces. HCMP = Older individuals with high conscious movement processing tendency; LCMP = Older individuals with low conscious movement processing tendency; SD = Standard Deviation. * $p < 0.05$.

appears to be independent of the environmental stressor. While HCMP inherently had higher T3-Fz EEG coherence under level-ground surface due to our analytical approach, such characteristic might consequently limit the extent of an increase in conscious movement processing from a normal walking environment to a more stressful one. One can argue that the limited increase could be attributed to the lack of stress induced by walking on an elevated walkway with an unstable surface, yet it is more likely that the higher baseline level of conscious involvement would have overloaded their working memory and thereby limiting HCMP from a further increase in cognitive engagement (R. Masters and Maxwell 2008; Wulf et al. 2001). HCMP's consistently higher T3-Fz EEG coherence suggests that their working memory resources may be heavily engaged even during walking on a normal environment, leaving less capacity for further cognitive engagement in handling additional stressors. An alternative interpretation grounded in Attentional Control Theory posits that heightened conscious movement processing in HCMP may act as an internal distractor, consuming attentional resources required for adaptively regulating stressors (e.g., excessive self-monitoring or verbal self-instruction could compete with external task demands) (Eysenck et al. 2007). While both working memory overload and attentional capacity limitations are plausible, their relative contributions require further studies to clarify their distinct roles in modulating conscious movement processing under stress.

In contrast, LCMP significantly increased real-time conscious movement processing under a challenging walking environment, as evidenced by a significant rise in T3-Fz EEG coherence with no significant change in T4-Fz EEG coherence. This suggests that the increase was specific to the engagement of verbal-analytical regions rather than global brain activation (Ellmers et al. 2016; Zhu et al. 2011). However, according to the rationale from the existing literature that older adults with a lower propensity to reinvest tend to allocate more attentional resources to the external environment (Uiga et al. 2015), one would expect that this cohort of older adults would be less vulnerable to increase conscious involvement of movement control. For instance, Mak et al. (2021) reported reduced real-time conscious movement processing when older adults were experimentally induced to allocate attention to the external environment even under a challenging walking environment. Our current findings, hence, offer differing evidence suggesting the theory that individuals with low baseline conscious movement processing can still succumb to environment-related increase in conscious processing of walking movements. While some may argue that this adaptation may intuitively serve as a protective mechanism for LCMP when experiencing stress, this could also impair motor behaviour and increase fall risks (R. Masters and Maxwell 2008; Uiga et al. 2020). Therefore, this observed response suggests the need to further investigate the implications on the potential fall risk in this particular cohort who are often assumed to have a lower risk of falling.

We propose that LCMP could benefit from gait training incorporating dual-task components, aimed at reducing cognitive load and enhancing the automaticity of walking. Engaging in walking training while concurrently performing a cognitive task, such as counting backward or naming objects, may divert

attention away from the conscious processing of walking mechanics. This approach is intended to facilitate the predominance of automatic motor processes, even in stressful situations. While these aspects have not been investigated, it highlights the need for future research to examine the association between dual-task performance/training and conscious movement processing in gait among older adults.

Contrary to the study's predictions, HCMP did not demonstrate poorer walking behaviour than LCMP when walking under a challenging environment, despite a significant reduction in neuromuscular efficiency (indicated by increased muscle co-contractions) and walking stability compared to walking under a normal environment. Specifically, HCMP demonstrated increased gait variability and M-L body sway, along with increased step width and slower gait. These findings align with Thies et al. (2005), who demonstrated that older adults on irregular surfaces adopted conservative strategies (e.g., slowing gait, widening step width) yet showed elevated gait variability—suggesting an inability to stabilise movement through motor control adjustments. This supports the hypothesis that heightened variability in older adults on unstable surfaces indicates a decline in gait performance, reflecting ineffective stabilisation rather than adaptive behaviour.

The mitigation of physical decline in HCMP could be a consequence of their significantly higher T4-Fz EEG coherence and/or lower CCI of thigh at baseline. The heightened T4-Fz EEG coherence suggests a potential association with heightened visual-spatial processing in HCMP (Zhu et al. 2011), which may reflect a greater adoption of visual-spatial strategies to navigate the challenging walking environment (Beurskens and Bock 2013). In line with previous research that reported an increased T4-Fz EEG coherence during a challenging walking environment (Mak et al. 2021), these findings cumulatively suggest that visual-spatial processing plays a contributing role in the cognitive resources necessary for regulating the control of locomotion, particularly when stress might have been induced (Menant et al. 2014). Such enhanced effort in visual-spatial motor planning could compensate for the negative physical outcomes of heightened conscious engagement. Furthermore, the relatively lower level of co-contraction on the thigh observed in HCMP at baseline may reflect reduced antagonistic muscle co-activation, which could contribute to improved movement efficiency by minimising unnecessary metabolic expenditure during challenging walks (Marques et al. 2013). Collectively, HCMP's reliance on visual-spatial motor planning—potentially reflecting heightened allocation of attention to environmental cues—may enhance their ability to pre-plan movements proactively (Uiga et al. 2020). This strategy is consistent with evidence suggesting that proactive, anticipatory postural strategies are associated with reduced muscle co-activation compared to reactive, compensatory strategies (Santos et al. 2010), hence leading to more efficient and automatic movements. Nonetheless, we postulate that this counteraction of conscious processing as an adaptation might only be specific to HCMP with a higher baseline level of physical function (those recruited in our study), based on the existing evidence that low-risk older adults are more capable of adopting proactive visuomotor strategies during walking (Ellmers et al. 2020). Future research should target older adults at a higher risk of falling, as the negative

impact of elevated conscious movement processing could be more pronounced in the absence of compensatory adaptations from higher physical function.

One potential limitation of this study is the reduced sample size resulting from tertile split analysis. Future studies should aim for larger sample sizes when employing this analytical approach. However, we do not consider this a major weakness as a further analysis has been conducted using baseline conscious movement processing as a continuous variable. The results were consistent with our current approach. For example, a lower baseline conscious movement processing tendency was associated with a greater real-time increase when stress might have been induced. Another limitation is the relatively high level of balance ability and mobility among the recruited older adults, limiting the generalisability of the findings to older adults with less optimal physical and psychological fall-related outcomes. We expect that older participants with poorer baseline balance ability would exhibit a higher level of baseline EEG coherence, and the physical decline in HCMP would be more apparent in the absence of compensatory adaptations from higher physical function. Future research could target older adults with a higher risk of falling to explore the potential differences between LCMP and HCMP in those groups where the use of visuomotor adaptation may be limited. While we used an elevated foam surface to induce stress based on its association with postural instability in prior work, we did not measure psychological or physiological stress responses (e.g., heart rate, respiratory frequency), leaving its anxiety-inducing effect unconfirmed. Future studies should validate this methodology to clarify the association between stress levels and conscious movement processing in older adults. Our use of one-second segments for EEG coherence computation also presents limitations, including low frequency resolution, susceptibility to noise interference, and the assumption of data stationarity, which may not hold during gait. Additionally, the current processing methods may not effectively filter out gait-induced noise. Future research should explore different segment durations and alternative noise removal techniques to ensure the acquisition of high-quality data. Lastly, future research could increase the complexity of walking tasks by adding a dual-task component, involving older adults with different psychomotor propensities and varying working memory capacities to deepen our insight into this area of study.

5 | Conclusion

This study provides valuable scientific insights into the distinctions in psychological and behavioural responses between older adults with different baseline conscious movement processing tendencies when environmental stress might have been induced (i.e., on an unstable surface). HCMP displayed consistently elevated levels of real-time conscious movement processing irrespective of the environmental stressor during walking, suggesting an overloaded working memory that constrains HCMP from experiencing a further increase in cognitive engagement, leaving limited capacity to adapt to additional stressors. Their unexpected reduced deterioration in behavioural outcomes seemed to be associated with a compensatory

visuomotor adaptation. LCMP exhibited increased conscious movement processing in response to environmental challenges accompanied by less stable and efficient walking behaviour. We suggest that even individuals with a low baseline conscious movement processing tendencies may still be susceptible to environmentally induced conscious movement processing. Our observation underlines the importance of investigating potential implications for fall risk in this cohort who are often assumed to have a lower fall risk, especially given the challenging walking conditions they might encounter in the community.

Acknowledgements

The authors would like to thank our collaborators Rich, Ada, and Catherine for their advice in the research proposal writing process. This work was supported by the General Research Fund from the Research Grants Council of the Hong Kong Special Administrative Region, China (Grant No. 15601021).

Ethics Statement

The study was approved by the Institutional Review Board of the Hong Kong Polytechnic University (PolyU IRB) (reference number: HSEARS20201126001).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data of this study are publicly available at [<https://osf.io/dbfwfp/>].

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.