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Strength of Plantar- and Dorsiflexors Mediates Step Regularity During a High Cognitive Load Situation in a Cross-sectional Cohort of Older and Younger Adults

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ABSTRACT

Background and Purpose: Completing simultaneous tasks while standing or walking (ie, a high cognitive load situation [HCLS]) is inevitable in daily activities and can lead to interference in task performances. Age-related physical and cognitive changes may confound performance variability during HCLS in older and younger adults. Identification of these confounding effects may reveal therapy targets to maintain optimal physical function later in life. The aim of this study was to investigate the effect of increasing the difficulty levels of an additional motor task and restricting visual information, on gait parameters in younger and older adults while considering the effect of cognitive and physical covariates.
Methods: Fifteen healthy younger and 14 healthy older adults were asked to complete assessments of cognitive function, balance, and strength. They were then asked to walk on a self-paced treadmill with or without carrying a plastic tray.
Opaqueness of the tray (vision) and the presence of water in glasses placed on the tray (increasing task difficulty) were varied. Mean, standard deviation, and regularity (sample entropy) of step width and length were compared across conditions and groups using repeated-measures analyses of variance with and without covariate analysis. Only significantly correlated covariates of cognition, balance, and strength were entered into each model.

Results and Discussion: Older adults had greater step width irregularity compared with younger adults across all conditions when controlling for concentric plantar- and dorsiflexion strength. A decline in strength may likely alter neuromuscular control of gait, specifically control of step width, which has been associated with fall risk in older adults. Adjusting for the same covariates revealed increased regularity of step length, as visual feedback from the feet was restricted. Specifically, step length was more regular while carrying an opaque tray compared with not carrying a tray. Visual restriction was a contributing factor, which led to more predictable gait kinematics, indicating the role of sensory information to enhance the adaptability during walking under HCLS.
Conclusion: The knowledge of the regularity behavior of human movement can expand physical therapists' treatment approaches to promote further interactivity and coordination across body systems that model behavior of healthy young individuals. Targeting strength during therapy may provide additional benefits for gait performance under HCLS.

Keywords: aging, entropy, gait, variability, vision

INTRODUCTION

Although walking is thought to be an automatic task, it requires attention and this demand increases with age.[1,2] As we age, a shift from unconscious to conscious information processing occurs,[3] and as a result, easy and/or automatic tasks, such as walking, become more difficult. If a second task is added to walking, this situation becomes more complicated, especially if the second task is also a motor task.[4] Competition for the same processing resources may lead to interference during high cognitive load situations (HCLSs).[4,5] Dual task is an example of HCLS under which a more difficult secondary task may lead to declines in the primary task performance.[6] High cognitive load situations repeatedly occur during everyday activities such as carrying grocery bags while talking and walking, or while searching in a bag during walking. These situations can add to the difficulty of the original task, which is walking. Decrement in gait performance while performing a secondary, attention-demanding task is associated with risk of experiencing a fall.[6] Serious consequences such as physical injuries, reduced functioning, social isolation, and mortality can result from a fall.[7]

Previous findings verify the effect of a concurrent secondary, cognitive task on walking performance.[8,9] However, there is limited research about performing a secondary, motor task while walking. Most studies in this area have been devoted to pathological populations such as patients with Alzheimer's disease,[10] Parkinson's disease,[11] and fallers.[12] Patients with Alzheimer's dis- ease walked slower and with more variability during dual-motor task conditions compared with single-task conditions.[10] Adding an attention-demanding, com- plex, and goal-orientated task (ie, carrying a tray with glasses) led patients with Parkinson's disease to take slower and shorter steps, and some participants reportedly stopped moving during the HCLS.[11] Fallers have significantly slower cadence and walking speed, longer stride time, and longer step length than nonfallers; however, nonfallers did not show significant differences between the single-task and dual-task conditions of carrying a glass of water during walking.[12] It is feasible that changes in healthy older adults' gait function under daily HCLS will be observed when compared with healthy younger adults. Investigation of these changes is important to determine the ability to balance during challenging walking conditions in this population. Moreover, if we find this age difference, it may suggest that increased vulnerability may appear with healthy aging, which is important to understand how normative age-related changes may influence gait, and indirectly fall risk.

In addition to the attentional resources needed for loco- motion, walking is a visually demanding task. The visual system provides information about the environment in which humans are moving.[13] Vision is a direct measure of self-motion, and it is typically used in avoidance or accommodation strategies for successful locomotion.[13] As we age, we become more dependent on vision, which could be a result of deficits in proprioceptive and vestibular senses in older adults.[14] Older adults benefit from visual cues as their spatial gait parameters were improved.[15] Velocity of locomotion is associated with vision in older adults.[16] When older adults walk, they look at the ground more than younger adults.[14] Tasks in everyday life may involve the obstruction of vision, or reduced ability to look at one's feet while walking, which can negatively affect gait and lead to increased risk of falls in all populations. Lack of sufficient visual cues while completing an HCLS may exacerbate gait performance deficits.

The aim of this study was to determine the effect of opaqueness of the tray (restricting vision) and the presence of water in glasses placed on the tray (increasing task difficulty) on walking performance in 2 groups of older and younger adults, while considering the effect of cognitive and physical covariates. It was hypothesized that increasing the levels of task difficulty and restricting visual input would negatively affect gait performance in both groups. These expected effects included wider step width and shorter step length, coinciding with increased variability and regularity. It was also predicted that the decline in gait performance during HCLS would be more considerable in older adults compared with younger adults.

METHODS

Participants

Thirty participants (15 younger [aged 19-35 years] and 15 older [aged 65-80 years]) were recruited to participate from the community. The sample size was chosen based on preliminary data of stride-to-stride variability and regularity between younger and older adults.[17,18] All participants were physically active, without any neurological or orthopedic disorders. Based on demographic questionnaires, participants were excluded from the study if they had any comorbidities that would affect walking ability, or neurological diseases like Parkinson’s, multiple sclerosis, or peripheral neuropathy. Moreover, previous injury or musculoskeletal problems such as knee injuries, low back pain, or severe arthritis led to exclusion. Anyone experiencing a fall in the last year, or unable to walk independently without an assistive device for at least a distance of 200 ft, was excluded. Pregnant women were not allowed to participate in the study. Participants were excluded if they did not have capacity to provide informed consent. After written consent was obtained, medical history and demographic data were collected for each participant. All procedures were reviewed and approved by the institutional review board at the university.

Apparatus and Procedure

The test procedure consisted of 2 sessions over 2 separate days within 1 month of each other. Assessments, representing potential covariates, were performed during the first session to evaluate cognitive function, balance, and muscle strength (Table). For cognitive function assessment, 3 tests from the Wechsler Adult Intelligence Scale-Revised (WAIS-R)[19]—digit span, digit symbol, and vocabulary—were used to assess cognitive functioning of memory, processing speed, and lexical level, respectively. Higher scores were indicative of better performance. Balance was evaluated using a sensory organization test (Neurocom Balance Manager, Pleasanton, California) providing a composite equilibrium score that quantified postural stability during 6 sensory conditions. Less movement of the center of pressure (decreased sway) was given a higher score, indicating better postural stability. Scores ranged from 0% to 100%. Participants also completed the Fullerton Advanced Balance Scale.[20] This performance-based measure addressed the multiple dimensions of balance, including static and dynamic balance activities performed in different sensory environments. Scores ranged from 0 to 40 and higher scores indicated better performance. Two major muscle groups (dorsiflexors and plantarflexors) of the ankle joint were tested bilaterally using an isokinetic dynamometer (Biodex 4.0, Biodex, Shirley, New York). Strength was measured at 60°/second for 5 maximum concentric contraction repetitions.[21] Any tests faster than 60°/second are considered to be power tests. Fast velocities do not allow the muscles enough time to produce elongated curves, while velocities under 60°/second may negatively influence the test due to the stress on joints, which may produce pain and reflex inhibition.[22] Peak torque to body weight on each side was recorded for each participant.

Table. Demographic and Covariate Data for the Participants Used in the Analysis

	Younger (n = 15) Mean (SD)	Older (n = 14) Mean (SD)	*P* Value
Age, y	20.6 (2.0)	70.6 (4.2)	$p < .001$
Body mass, kg	65.0 (12.8)	75.0 (16.2)	.075
Height, m	1.7 (0.1)	1.7 (0.1)	1.0
WAIS vocabulary (points)	39.5 (7.3)	42.3 (10.1)[a]	.397
WAIS digit span (points)	16.2 (3.6)	17.5 (5.0)[a]	.446
WAIS digit symbol (points)	88.7 (12.0)	58.9 (15.8)[a]	$p < .001$
SOT equilibrium score, %	72.2 (8.1)	74.9 (4.2)	.283
Fullerton Advanced Balance (points)	38.9 (1.4)	33.8 (6.0)[a]	.004
Right dorsiflexion, Nm/kg	11.7 (2.3)	8.2 (2.2)	$p < .001$
Left dorsiflexion, Nm/kg	11.6 (2.5)	8.6 (2.0)	.002
Right plantarflexion, Nm/kg	19.2 (7.9)	11.3 (7.9)	.011
Left plantarflexion, Nm/kg	21.7 (10.9)	12.2 (12.0)	.035

Abbreviations: SOT, sensory organization test; WAIS, Wechsler Adult Intelligence Scale.
[a]Based on n = 13 for older adults due to one participant not completing the tests. For all other measures, data from 15 younger and 14 older adults were used.

During the second session, all participants walked on a self-paced treadmill at their normal pace,[23] while lower extremity kinematic data were recorded (Nexus, Vicon, Oxford, UK; 100 Hz). The treadmill, which was used in this study, was motorized. The motion capture system was used to monitor the walking speed of the participant, which was used to update the motor speed in real time to accommodate natural fluctuations in gait.[24] (More information regarding this particular system can be found in our published articles.[23,25]) This treadmill partially removes the normal constraints imposed by a fixed-speed treadmill to allow for a more natural variation of walking speed.[25,26]

While wearing a form-fitting suit, retroreflective markers were placed on the toe, heel, and malleolus of each foot. Participants were secured in an overhead harness system (Solo-Step, Inc, North Sioux City, South Dakota). After a 5-minute adaptation period and once participants indicated they were comfortable, experimental conditions were per- formed. Experimental conditions with abbreviations are as follows:

- Baseline: baseline
- Clear tray: C-W/O
- Clear tray and glasses: C-W
- Opaque tray: OP-W/O
- Opaque tray and glasses: OP-W

During each condition, the participants were instructed to walk on the self-paced treadmill for 3.5 minutes at their normal pace without any additional instruction. The baseline condition was considered the single task, in which the participant walked normally on a self-paced treadmill. During the HCLS conditions, participants were asked to carry a light-weight plastic tray (clear [360 g] or opaque [600 g]) while walking with 2 levels of task difficulty, with or without 4, 1-oz glasses filled ¾ full with water sitting on top of the tray. The glasses were arranged in a square shape evenly distributed on the tray according to Figure 1. Glasses were a set distance apart (10 cm), and locations were marked on the tray to be consistent. After the baseline condition, the 4 remaining conditions were performed in randomized order. There was 1 trial per condition and a minimum 2-minute rest between each trial.

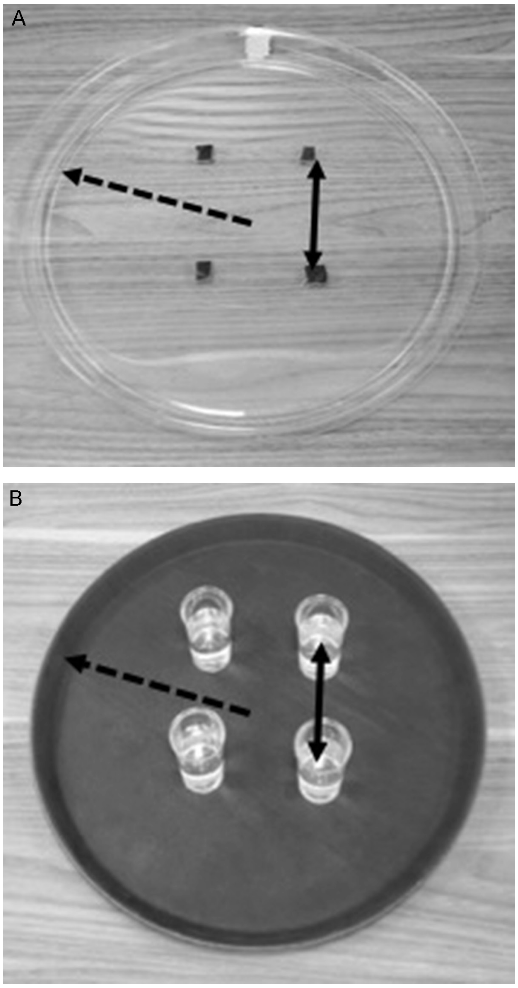
A
B

Figure 1. Clear (A) and opaque (B) tray dimension and glass positions used for the experiment**.** The radius of the tray, as indicated by the dashed arrow, was 16 cm in length. The distance between each of the glasses was standardized to 10 cm, indicated by the solid arrows. Glass positions were standardized using small tape marks on the trays.

Data Analysis

The first 60 seconds of the collected data were excluded to avoid nonstationary of data caused by walking on a self-paced treadmill. For assessment of gait performance, step length and step width were calculated. Step length was defined as the distance from the heel strike of one heel to the heel strike of the contralateral heel. Step width was defined as the mediolateral distance between the left and right subsequent heel strikes. The step length and step width time series from each of the 5 conditions for every participant were utilized for analyses. Mean and standard deviation values for step length and step width were calculated for each time series and were not significantly different between right and left legs. Thus, reported data represent the average of left and right sides.

Sample entropy of the time series for both legs was calculated and averaged to represent changes in pattern of movement over time during different HCLS conditions. Sample entropy[27] was defined as the probability of future patterns to be close to the previous ones and provided regularity evaluation of human movement.[28] We used the parameter values $m = 2$ and $r = 0.2 \times$ standard deviation for calculation of sample entropy after examining the relative consistency with $r = 0.15$ and $r = 0.25$. A sample entropy value close to zero indicated a highly regular system, whereas irregularity increased with larger values.

High cognitive load costs of gait were calculated for each parameter and for each effect in supplemental material using the following equation:

$$\text{High Cognitive Load Cost} = \frac{(\text{Lower Cognitive Load Performance}) - (\text{Higher Cognitive Load Performance})}{\text{Lower Cognitive Load Performance}} \times 100$$

The equation is the modified version of the interference equation proposed by Plummer and Eskes.[29] The equation was modified for the purpose of high cognitive load cost rather than single- versus dual-task conditions. Tray motion data were calculated using acceleration resultant vector (see the Supplemental Digital Content, available at: http://links.lww.com/JGPT/A41). Sample entropy and standard deviation of the acceleration vector were quantified and compared across groups and conditions. Further information about high cognitive load cost and tray motion can be found in the online supplementary materials. All calculations were performed using custom MATLAB programs (The MathWorks, Natick, Massachusetts).

Statistics

Data were inspected for normality. Normally distributed data allowed the use of repeated-measure analyses of variance for identification of differences in each dependent variable between groups and conditions, including investigation of interactions between groups, increasing the levels of task difficulty, and restricted visual input factors (using an opaque tray).

Models were run with and without significant covariates to determine whether adjusting for cognition and balance affected the performance. Correlations between outcome variables at baseline and potential covariates were calculated. Variables with a correlation of at least 0.3 with a given outcome were included as a covariate in modeling procedures. Potential covariates included the WAIS-R digit span, symbol, and vocabulary, Neurocom composite balance score, Fullerton Advanced Balance, and the strength of plantar- and dorsiflexors. Those significantly correlated with baseline (walking only) gait variables were included as covariates in the repeated-measures model. Adjustments for multiple comparisons were made using the simulation technique, the recommended approach for data with repeated measures. The level of significance was set at .05.[30] Analyses were conducted using SAS (SAS Institute, Inc, Cary, North Carolina).

RESULTS

One older participant was excluded due to difficulty walking on the self-paced treadmill; thus, only 14 older adults' data were included in the analysis. Out of the 14 older adults, 1 older adult did not complete the cognitive function assessment; however, all walking tasks were completed for that participant (Table). No participant spilled water and glasses were not moved after each trial. For results of high cognitive load cost, please see the Supplemental Digital Content (available at: http://links.lww.com/JGPT/A41). No differences in cost were found (see the Supplemental Digital Content, Table S1, available at: http://links.lww.com/JGPT/ A41).

Mean and Variability

Increasing task difficulty (adding glasses of water on top of the tray) and reduced visual input (using an opaque tray) did not significantly affect mean and standard deviation of gait values between conditions or between groups (Figure 2).

Significantly correlated covariates of Fullerton Advanced Balance, WAIS digit span, WAIS digit symbol, and strength of plantarflexors were used in the covariate analysis. Results from the covariate analysis indicated that step width standard deviation demonstrated a significant 3-way interaction group × tray × glasses ($F_{1,101} = 4.6$; $P = .035$). However, in follow-up pairwise comparisons, no significant differences were observed.

Regularity

No significant main effects or interactions were found for increasing levels of task difficulty and restricted visual input between conditions nor between groups for step length or step width regularity (Figure 3). Significantly correlated variables used in the covariate analysis were the strength of plantar- and dorsiflexors. Adjusting for strength covariates, step width sample entropy revealed a main effect of group ($F_{1,26.1}$= 5.4; P = .028). The older adults had a more irregular step width than younger adults across all tray and glass conditions. A difference in step length regularity was observed between tray conditions (no tray to clear tray to opaque tray) ($F_{2,105}$= 7.9; P < .001). Post hoc tests revealed that the step length during the opaque tray condition was significantly more regular than the no tray (baseline) condition for both groups and glass conditions (P < .001).

Tray Motion

Tray motion became less variable (lower standard deviation) by adding glasses on top of the tray (P = .002; see the Supplemental Digital Content, Figure S1, available at: http://links.lww.com/JGPT/A41). Tray motion became more irregular (greater sample entropy) by adding glasses on top of the tray (P < .001). Moreover, tray motion during opaque tray conditions was more regular than the clear tray conditions (see the Supplemental Digital Content, Figure S1, available at: http://links.lww.com/JGPT/A41).

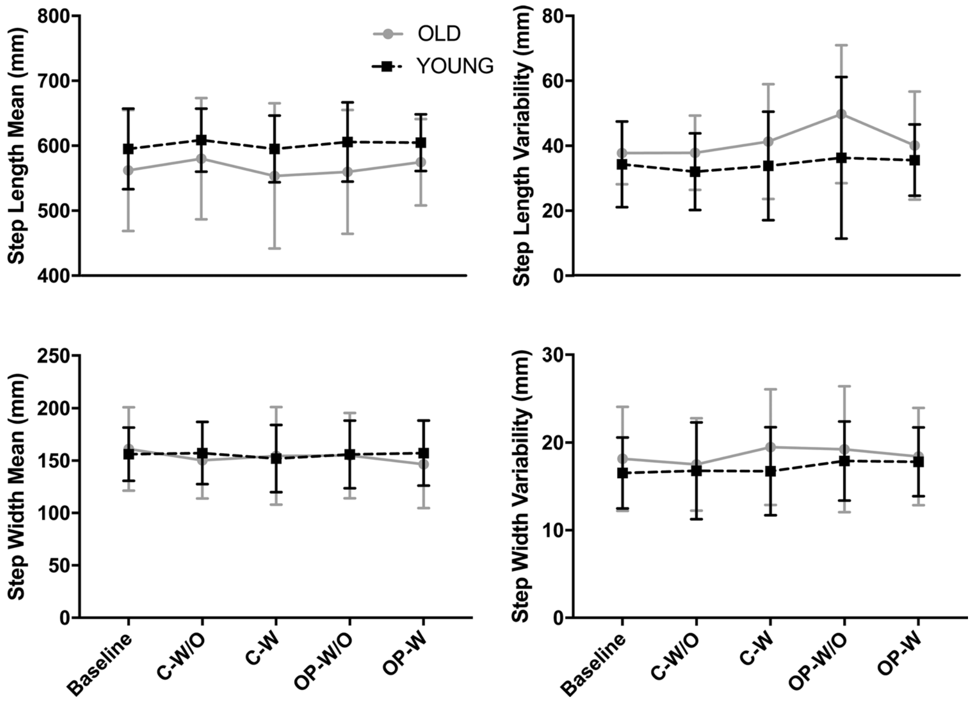

Figure 2. Spatial gait parameters' (step length and step width) means (left) and variability (right) during different walking conditions. Gray solid line represents the values for older adults and dashed black lines are indicating the values for younger participants.

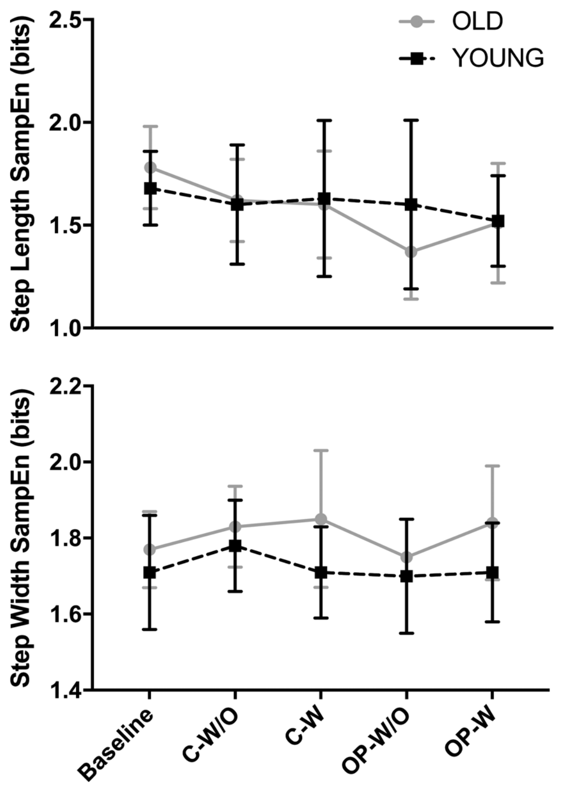

Figure 3. Sample entropy of spatial gait parameters during different walking conditions. Gray solid line represents the values for older adults and dashed black lines are indicating the values for younger participants.

DISCUSSION

The aim of the present study was to examine the effect of increased levels of task difficulty (adding glasses of water on top of the tray) and restricted visual input (using an opaque tray) while walking in younger and older healthy adults, while considering the effect of covariates. Overall, the results partially supported the hypothesis. No differences in step width mean, step length mean, or step length variability were found. A significant interaction for step width variability was found; however, not significant upon post hoc analysis. The novel finding of this study was that older adults walked with a more irregular step width pattern compared to younger adults regardless of the condition. Further, both groups' step length regularity was affected by the opaque tray. Step length was more regular when walking with the opaque tray than with no tray.

Although traditional variability measures (eg, standard deviation) provide information about the amplitude and dispersion of data, they are unable to reveal the temporal structure of changes in a movement pattern. A healthy system fluctuates and has natural irregularities.[31] Movements that are too regular are considered rigid, while more irregular or random movements are highly unpredictable.[32] Both reflect a system likely to lack adaptability to task and/or environmental changes. Using measures designed to identify regularity differences between age groups may be useful for assessing increased vulnerability that may appear with age—as traditional measures may not reveal differences as in the current study. Contrary to the theory of over regularity (decreased entropy) in the presence of age and disease,[33] the present study found that older adults walked with a more irregular step width compared with younger adults. A more irregular gait pattern has been demonstrated in older adults with knee osteoarthritis[34] and in those with a risk of fall compared with healthy controls.[35] Less regularity of stepping patterns may indicate increased randomness and loss of gait control.[35]

Differing to the findings in step width, when walking with an opaque tray, all participants, no matter their age, walked with a more regular step length pattern. The increased regularity of movement while carrying the opaque tray could have been due to visual obstruction of the feet. Increased task demands lead to a more continuous visual regulation of gait based on the visual information available for foot placement.[36] Another explanation could be due to increased reliance on passive dynamics during the opaque tray condition. Properties of the limbs in the anterior posterior direction are more likely to depend on passive dynamics.[37] In the presence of sensory restriction, it is feasible that attention was diverted from the anterior posterior direction, increasing reliance on passive dynamics, and increasing resources available to attend to the mediolateral direction—a direction associated with balance.[38] This strategy would ensure stability throughout the walking trial. Thus, restricting visual information may have required a shift in visual allocation and/or attention, resulting in increased reliance on passive mechanisms and ultimately a more rigid step length pattern.

Alternatively, diverting attention away from walking may have allowed more attention to be paid to the secondary task of tray carrying. Tray motion became more regular and less variable in the opaque tray condition (see the Supplemental Digital Content, Figure S1, available at: http://links.lww.com/JGPT/A41). Models have been developed to explain the effect of attention on performance under HCLS. Central capacity or resource-sharing models suggest that the sum of attention demands of component tasks should not exceed the available resources of attention. Based on this model, task complexity, familiarity, and importance can influence divided attention.[39] In the current study, both tray performance and walking on the self-paced treadmill were highly visual dependent, and may have been using the same input or output of the system. This may have caused overloading of system capacity and led to structural interference. Due to this structural interference, the impact of HCLS in this study may not be solely related to competing available resources of attention but could be due in part to the competing visual input/modality under HCLS.

The use of regularity measures is relevant to the field of rehabilitation. Knowing the regularity behavior of human movement can expand physical therapists' treatment approaches to include those promoting interactivity and coordination across body systems that model behavior of healthy young individuals.[32] At this time, there are no known commercially available, clinical, rehabilitation tools that directly measure regularity. Although systems are in development, advocating for their need to further the field of rehabilitation is important. Previous calls for the use of regularity measures to access changes in movement regularity of patients' function to determine improvement with an intervention or possibly deterioration in the presence of pathology have been made.[32] To account for complex interactions within the physiological system, the regularity of movement patterns should be considered while designing interventions.[31]

It is important to note that muscle strength loss in older adults mediated step regularity in this population. Loss of shank muscular strength due to aging may lead to a disruption in the neuromuscular control of walking, which affects the stability of walking patterns. Reduced synthetic rate of muscle proteins,[40] as well as the muscle's ability to repair, is associated with sarcopenia in aging.[41,42] Decline in muscle strength in the aging population is consistent across all measurements and muscle groups, which are associated with fear of falling in older adults.[43] Even in the oldest cohort of older adults, exercise training has been shown to be effective to improve both muscle size and voluntary strength.[44,45] Training to strengthen the ankle joint was effective to enhance the gait ability of older adults at risk of falls,[46] and plantar muscle strength was shown to be important in fall prevention in older adults.[47] These findings are in agreement with other studies showing that lower extremity muscle strength is strongly associated with gait speed,[48,49] adding to the link existing between strength and lower extremity function.[50] The improvement of strength as a target in physical therapy could potentially improve gait under HCLS conditions, especially in persons of older age.

There are several limitations to this study. First, participants may not have been equivalent with regard to cognition, visual acuity, use of bifocals, comorbidities, and fall risk. Although cognitive function, balance, and muscle strength were recorded as potential covariates, differences were found in the Fullerton Advanced Balance Scale and the WAIS Digit Symbol performance between groups. Furthermore, visual acuity and use of bifocals were not recorded, and comorbidities not specifically asked about may have been present and not reported. In general, the older adults were approximately 70 years old, were living independently, and were active and reported themselves as healthy. In the future, participants could be divided between those who scored lower versus higher on cognitive function. This could be especially useful given the link between gait and cognitive functioning. It is possible that those who perform lower on cognitive tasks suffer more during HCLS. Second, the use of a motorized, self-paced treadmill necessitated a sufficient adaptation period, especially for older adults to acclimate to their usual gait pattern. The adaptation period was standardized for all participants, and it is unknown whether all participants adapted to the treadmill within that time. To control for this, the first 60 seconds was removed to eliminate this inconsistency. In and of itself, the use of a self-paced treadmill could be a separate task (competing visual information). However, the use of a treadmill was necessary to answer the research question. Regularity calculations require numerous data points that are continuous in nature. As motion capture is limited during overground walking, a treadmill was required. However, the treadmill used in this study may have allowed more natural fluctuations in gait behavior.[51,52] Third, although both trays were lightweight, the opaque tray was heavier than the clear tray while their sizes were identical. Fourth, dual-task costs are commonly calculated in studies of HCLS. Although they were calculated in this study, no significant differences were found between age groups (see the Supplemental Digital Content, Table S1, available at: http://links.lww.com/JGPT/A41). Minimal detectable changes in high cognitive load cost are dependent to the person's absolute measures and the nature of tasks, which are being combined. Evaluating the respective gait and cognitive differences in the pattern of interference for each task individually and comparing against each other can reveal the interaction between multiple tasks.

CONCLUSIONS

The aim of this study was to investigate the gait changes under HCLS in 2 healthy groups of participants (younger and older adults) when task difficulty was increased, or visual input was restricted. When controlling for plantar- and dorsiflexor strength, it was found that step width was more unpredictable in the older adults compared with the younger adults. Further, after controlling for muscle strength, step length was affected by the restriction of vision with an opaque tray, becoming more rigid as visual information was restricted. Increasing physical therapists' access to tools that can measure regularity would expand the treatment approaches to include interventions with the aim of promoting interactivity and coordination across body systems. Additionally, developed interpretation of mechanisms and behavior underlying HCLS may lead to enhanced treatment processes in specific situations and pathological conditions.[29] Methods of interventions could be customized for each age group, or pathological condition considering behavioral changes during HCLS.

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