

The Fukuda Stepping Test Is Influenced by a Concurrent Cognitive Task and Step Height in Healthy Young Adults: A Descriptive Study

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ABSTRACT

Purpose: The Fukuda stepping test assesses spatial orientation in people with vestibular disorders. To standardize the test, it is important to know which factors influence the outcome. This study investigated the impact of two factors, a concurrent cognitive task and step height, on the Fukuda stepping test in healthy individuals. **Method:** A total of 16 young adults participated and completed 20 trials of the 50-step Fukuda stepping test in four conditions: comfortable and high step height and with and without a cognitive task. Body kinematics were collected using the three-dimensional motion analysis Vicon system. The cognitive task was to listen to a sequence of three-digit numbers and identify the total number of times that one pre-determined digit was presented. **Results:** All participants slowly turned and drifted forward during the test. The concurrent cognitive task yielded significantly shorter forward displacement and lateral deviation and lower stepping height, and high stepping produced significantly greater body rotation and lateral deviation. **Conclusions:** Performance on the Fukuda stepping test in healthy young individuals is influenced by a concurrent cognitive task and by step height. Clinicians and researchers must instruct people to use a comfortable step height during the test, and they must be aware that a concurrent cognitive task may improve test performance, at least among young adults.

Key Words: body kinematics; dual task; focus of attention; orientation; stepping in place.

RÉSUMÉ

Objectif : le test de Fukuda évalue l'orientation spatiale chez les personnes ayant une pathologie vestibulaire. Pour le standardiser, il est important de connaître les facteurs qui influencent le résultat du test. La présente étude portait sur l'impact de deux facteurs, une tâche cognitive et la hauteur des pas sur le test de Fukuda chez des personnes en bonne santé. **Méthodologie :** au total, 16 jeunes adultes ont complété les 20 essais du test de Fukuda de 50 pas dans quatre conditions : pas d'une hauteur confortable ou élevée, accompagné ou non d'une tâche cognitive. Les chercheurs ont enregistré la cinématique à l'aide du système Vicon d'analyse du mouvement en trois dimensions. La tâche cognitive consistait à écouter une série de nombres à trois chiffres puis à établir le nombre d'apparitions d'un chiffre prédéterminé. **Résultats :** tous les participants ont tourné et avancé lentement pendant le test. L'ajout de la tâche cognitive était lié à un déplacement et une déviation latérale moins marqués et à un pas moins élevé. Un piétinement élevé était associé à une rotation du corps et une déviation latérale plus importantes. **Conclusion :** la performance au test de Fukuda est influencée par une tâche cognitive simultanée et par la hauteur du pas chez de jeunes adultes en bonne santé. Les cliniciens et les chercheurs doivent expliquer qu'il faut adopter une hauteur de piétinement confortable pendant le test et ils doivent savoir qu'une tâche cognitive simultanée peut améliorer la performance, du moins chez les jeunes adultes.

Mots-clés : focus d'attention; cinématique; double tâche; orientation; marche sur place.

People with inner ear (or vestibular) disorders experience dizziness, vertigo, vision troubles, and balance impairments.¹ Examples of vestibular conditions are vestibular neuritis, acoustic neuroma, ototoxicity, and abnormal vestibular function due to concussion. Vestibular rehabilitation is a physiotherapeutic approach to assessing and treating symptoms and impairments in these patients and for improving their quality of life.²

The Fukuda stepping test is one of a battery of tests physiotherapists use to assess patients with vestibular disorders and patients with dizziness.^{1,3} The test has a patient step in place at a comfortable cadence while blindfolded, with the instruction to stay in the same spot and not turn. The number of steps is usually 50,⁴⁻⁷ but some studies have reported a 20 step-test and a 100 step-test.⁸⁻¹¹ An alternative procedure is to step for a specified

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time of 30 seconds or 1 minute.¹²⁻¹⁴ The main clinical outcomes are the direction (to the left or right) and amplitude of body rotation. However, previous studies have also investigated linear body displacement.¹⁵⁻¹⁷

Patients with unilateral vestibular hypofunction exhibit body rotation and body displacement during the Fukuda stepping test.^{4,5,7} Body rotation is presumed to occur because vestibulospinal output exerts ipsilateral tonic control on the antigravity muscles, and this control is impaired with unilateral vestibular hypofunction.¹⁸ Specifically, vestibulospinal tonic control would be reduced on the affected side, and lower limb loading would be uneven, with more loading on the affected side. As a result, body rotation would occur when stepping in place with the vision obscured.¹⁹ Body displacement is presumed to reflect the limits of path integration, which is the sensorimotor function at play when a blindfolded individual keeps track of their current position with reference to the starting point.²⁰

Interestingly, body rotation and linear body displacement are also observed in healthy individuals.^{9-10,13} This suggests that the Fukuda stepping test does not specifically assess the integrity of vestibulospinal function. Recently, the test has been related to spatial orientation functions,²⁰ which involve the integration of vestibular, proprioceptive, and tactile inputs, as well as neurocognitive processes.²¹ In fact, various sensory stimulations, such as those of the neck muscles,¹⁴ galvanic vestibular stimulation,²² auditory stimulation,¹⁶ and ankle loading,²³ have modified body rotation and linear displacements among healthy participants during stepping on the spot without being able to see. However, a possible effect of a concurrent cognitive task has yet to be studied, even though cognitive functions are known to be involved in spatial orientation and navigation.²⁴

During quiet standing, concurrent cognitive tasks were found to decrease body sway in young adults, suggesting that postural control was improved in dual-task conditions in this population.²⁵⁻²⁶ According to the constrained action hypothesis,²⁷ a cognitive task directs a portion of the attention away from the control of posture, resulting in more automatic and efficient control. However, another study has shown deterioration of gait control under dual-task conditions in young adults.²⁸ This may be due to limited attentional resources and surpassed attention capacity when two tasks that require attention are performed concurrently. As a result, performance on one or both tasks is impaired, as proposed by the capacity-sharing theory for information processing.²⁹⁻³¹ In this study, we investigated whether a concurrent cognitive task could influence the outcome on the Fukuda Stepping test.

Another factor that may influence the test is step height. Stepping with high knees is likely more challenging for balance than stepping at a comfortable knee height. Lifting the knees high requires a stronger contraction of

the hip flexor muscle of the lifted leg, together with more demanding hip and ankle muscle control of the supporting leg in all directions to maintain single-leg stance. Moreover, the effort of stepping high may increase the task's attentional demand compared with stepping at a comfortable height. As a result, the ability to stay in the same spot during the test may be affected, which would be evidenced by an increase in body rotation and linear displacement. We also investigated whether stepping with high knees could influence the outcome of the test.

Performing concurrent cognitive tasks and lifting the knees high are not normally used with the Fukuda stepping test, and we are not proposing that these conditions be incorporated into it. This study is useful because it enables us to better understand two factors that may influence test outcome and, ultimately, to provide more specific and standardized instructions to patients and research participants. The specific aims of this study were to determine the effect of performing a concurrent cognitive task while performing the 50-step Fukuda stepping test on body rotation and forward and mediolateral displacements as well as to determine the influence of step height on these parameters.

METHODS

Study design and setting

This was a quantitative, cross-sectional, descriptive study. Testing sessions took place in a large, quiet room in a university campus building.

Participants

A total of 16 young adults (12 women, 4 men) aged 20–26 years (mean 22 y) were recruited using advertising posters and word of mouth. The sample size was estimated from the rotation variability obtained in a previous study (SD 6.9°),¹⁵ and a clinically worthwhile difference of 8°. A sample of at least 12 participants was needed to achieve an α of 0.05 and a power of 0.80.³²

The participants' weight ranged from 49.0 kilograms to 81.8 kilograms (mean 63.0 kg), and their height ranged from 1.55 metres to 1.78 metres (mean 1.66 m). Participants were excluded if they had a musculoskeletal injury in the previous 6 months and were experiencing pain or discomfort, particularly in their back or lower limbs; or if they had dizziness or vertigo in the previous 6 months; or if they had any neurological condition. Previous studies have shown that footedness has a significant influence on the direction of body rotation during the Fukuda stepping test.^{10,13} Thus, the Waterloo Footedness Questionnaire was administered to prospective participants, and only those who had right foot preference as determined by a score between 11 and 20 were included.³³

All participants signed an informed consent form approved by the University of Ottawa Research Ethics Board.

Procedures

All participants were tested by JG. Before being tested, they walked around and stepped in place for a few minutes with their vision completely obscured by opaque goggles to acclimatize themselves to the testing conditions. The testing session consisted of 20 trials of the 50-step Fukuda stepping test with the participants keeping their arms at their sides. They wore a tight t-shirt or tank top, tight shorts or leggings, and socks. Each trial lasted approximately 30 seconds, and the whole testing session lasted approximately 1 hour. To avoid fatigue, the participants could take a break at any time.

There were four conditions: comfortable step height (CStep), high stepping (HStep), comfortable step height with concurrent cognitive task (CStep+CT), and high stepping with concurrent cognitive task (HStep+CT). The first 10 trials were completed at a comfortable step height with the five CStep and the five CStep+CT trials randomized. The next 10 trials were completed at high stepping; the five HStep and the five HStep+CT trials were randomized.

For the CStep condition, the examiner demonstrated to the participants a comfortable and natural stepping style with approximately 45° of hip flexion and at approximately 1.9 steps per second. For the HStep condition, the examiner demonstrated the task with the hip flexed at approximately 90°. Participants were given the following instructions for all trials:

Put on the blindfold. At the signal “Start,” start stepping. Always stay on the same spot during the 50 steps. Do not count the steps. They will be counted by the examiner, who will say “Stop” out loud when the 50 steps are completed. Stop stepping and stay in place for 5 seconds.

At the end of each trial, the participants kept the opaque goggles on and were guided back by the examiner to the starting position, taking a different path each time. They did not return to the start position by simply backing up because this would have given them clues about their unperceived body displacement.

The concurrent cognitive task was a silent counting task in which the participants wore Bluetooth-operated, noise-reducing headphones. A sequence of three-digit numbers was presented every 2 seconds (e.g., 468-724-915-073-548) for the duration of the 50 steps, and participants were asked to identify the total number of times that one pre-determined target digit (e.g., 4) was presented. The participants gave their answer to the examiner when they completed the trial. Each trial used a different target digit.

The participants were instructed that the two tasks were of equal importance – that is, counting and staying on the spot while stepping. The aim was for them to pay an approximately equal amount of attention to both tasks rather than focusing only or excessively on one

or the other because this could have introduced large between-subjects variability in the dual-task focus of attention. Consequently, a range of 50% above or below the correct answer to the cognitive task was accepted, and a trial was excluded from our data analysis if a participant gave a number that differed from the correct answer by 50% or more – for example, if the target digit was repeated 11 times during a trial, but the participant’s answer was 5 or less or 17 or more.

Data collection and analyses

Kinematic data were recorded with seven infrared cameras using Vicon motion-capture technology (Vicon Motion Systems, Denver, CO). A set of 14 reflective markers was fixed to each participant and used to capture their position. We then analyzed the data from the right and left shoulder (acromion) and knee (tibial plateau) markers. Marker positions in the frontal, sagittal, and vertical planes were sampled at a rate of 200 Hz.

The duration of each trial was the time between the moment of the first vertical displacement of the right knee marker (first step) and the moment of the lowest vertical displacement of the left knee marker (50th step). Stepping frequency in steps per second and cadence in steps per minute were calculated from the duration of the trial. Stepping height was the difference between the highest and the lowest vertical position of the knee for each of the 50 steps. Because there was no significant difference in stepping height between the two legs, combined left-right stepping height was calculated and reported.

The participants’ final position at the end of the trials was used to calculate body rotation and linear displacement. Body rotation was obtained first by defining a line connecting the two shoulder markers, then by calculating this line’s angle at the final position relative to the starting position. Clockwise rotation was given a positive value; counterclockwise rotation, a negative value. Linear displacement was obtained by defining a centre point between the two shoulder markers and gathering its coordinates (X and Y) on the horizontal plane at the final position. Sagittal displacement was systematically in the forward direction and was named forward displacement. Lateral deviation was identified as mediolateral displacement; displacement to the right was given a positive value; displacement to the left, a negative value.

For trials that included the cognitive task (CStep+CT and HStep+CT), the participants were asked to self-report their attentional focus by assigning a percentage value to how much attention they had allotted to the counting task relative to the stepping task.

Statistical analyses

To test the main effects of two independent variables, cognitive task and step height, and their possible interactions, we performed a repeated-measures analysis of variance with two within-person factors – cognitive task

(two levels: with [CStep+CT and HStep+CT] and without [CStep and HStep]) and step height (two levels: comfortable [CStep and CStep+CT] and high [HStep and HStep+CT]) – on stepping frequency, cadence, stepping height, body rotation, forward displacement, and mediolateral displacement. The paired *t*-test (two-tailed) was used to compare self-reported attentional focus between the CStep+CT and HStep+CT conditions. All statistical analyses were performed using IBM SPSS Statistics (Version 26; IBM Corporation, Armonk, NY). Statistical significance was set at $p \leq 0.05$.

RESULTS

We found no significant influence of the participants' characteristics on body rotation, linear displacement, or stepping height. None of the participants had concerns about a possible loss of balance, and no loss of balance occurred during testing. No one asked for a rest during their session. No participant exceeded the acceptable range of scores for the cognitive task, and no trial was excluded for this reason. Participants gave the correct

answer in most trials (73%), made one or two errors in 25% of trials, and made three or four errors in 2% of trials.

Stepping characteristics

The test results are provided in Table 1. We found a significant main effect of the cognitive task on stepping height ($F_{1,77} = 58.55$, $p = 0.001$, $\eta^2 = 0.43$) and a significant interaction between cognitive task and step height ($F_{1,77} = 7.29$, $p = 0.009$, $\eta^2 = 0.09$). For both comfortable and high stepping, stepping height was lower when performed with the cognitive task than without it.

Body rotation

The values in Table 1 show that body rotation was clockwise in about half the trials and counterclockwise in the other half. As a result, mean body rotation (signed values) was approximately 0° , with a large SD. To better describe the amplitude of body rotation regardless of direction, absolute values (unsigned values) were calculated and reported. There was a significant main effect of step height on body rotation (unsigned values) ($F_{1,76} = 20.28$, $p = 0.001$, $\eta^2 = 0.21$), but no main effect of

Table 1 Group Performance on the Stepping Task

Test characteristic	Mean (SD)*			
	CStep	CStep+CT	HStep	HStep+CT
Duration, s	29.9 (3.7)	29.6 (3.9)	31.7 (3.8)	31.6 (3.5)
Frequency, steps/s	1.7 (0.2)	1.7 (0.2)	1.6 (0.2)	1.6 (0.2)
Cadence, steps/min	100.2 (12.6)	101.4 (13.8)	94.8 (11.4)	94.8 (10.8)
Stepping height, cm ^{††}	15.0 (5.8)	13.8 (5.2)	31.1 (11.3)	29.9 (9.6)
Stepping height, 95% CI	12.9, 17.0	12.0, 15.7	27.0, 35.1	26.5, 33.4
Body rotation				
Unsigned values, degrees [§]	23.3 (18.7)	19.3 (17.1)	30.0 (24.2)	30.6 (25.0)
95% CI	19.0, 27.5	15.4, 23.2	24.5, 35.5	25.0, 36.3
Signed values, degrees	-0.3 (29.9)	-0.8 (25.9)	1.4 (38.3)	-5.3 (39.5)
Range, min–max, degrees [¶]	0.2–106.1	0.6–76.9	0.6–137.4	1.4–116.7
Clockwise, % of trials	48.1	50.0	45.6	44.3
Forward displacement				
Distance, cm [†]	70.8 (32.9)	64.7 (30.0)	65.3 (39.9)	56.5 (39.5)
95% CI	63.2, 78.3	57.9, 71.6	56.2, 74.5	47.5, 65.6
Range, min–max	6.1–145.9	5.0–128.0	5.0–175.0	0.8–154.4
Mediolateral displacement, cm				
Unsigned values ^{†§}	16.7 (14.2)	12.7 (11.0)	22.6 (17.8)	19.9 (15.7)
95% CI	13.5, 19.9	10.2, 15.2	18.6, 26.7	16.3, 23.4
Signed values	2.0 (21.8)	2.2 (16.3)	3.2 (28.1)	0 (25.2)
Range, min–max, degrees [¶]	0–65.4	0.1–53.9	0.7–86.6	0.3–67.7
Attentional focus, cognitive/stepping, % [§]	N/A	68.4 (13.9)	N/A	55.6 (10.1)

* Unless otherwise indicated.

† Significant main effect of the cognitive task.

‡ Significant interaction of the cognitive task with step height.

§ Significant main effect of step height.

¶ From unsigned (absolute) values.

CStep = comfortable step height; CStep+CT = comfortable step height with concurrent cognitive task; HStep = high stepping; HStep+CT = high stepping with concurrent cognitive task; N/A = not applicable.

the cognitive task and no interaction. Body rotation was larger at high stepping than at comfortable stepping.

Forward and mediolateral displacements

Table 1 lists the values for forward and mediolateral displacements. There was a significant main effect of the cognitive task on forward displacement ($F_{1,75} = 31.33$, $p = 0.001$, $\eta^2 = 0.30$) and on mediolateral displacement (unsigned values) ($F_{1,75} = 8.93$, $p = 0.004$, $\eta^2 = 0.11$) but no interaction. Forward and mediolateral displacements were shorter when performed with the cognitive task than without it. There was a significant main effect of step height on mediolateral displacement (unsigned values) ($F_{1,75} = 15.75$, $p = 0.001$, $\eta^2 = 0.17$) but no interaction. Mediolateral displacement was larger at high than at comfortable stepping.

Attentional focus

The values for attentional focus are also listed in Table 1. The percentage of attentional focus that was allocated to the cognitive task was significantly lower at high (HStep+CT) than at comfortable stepping (CStep+CT) ($t_{15} = 3.29$, $p = 0.005$).

DISCUSSION

This study had three main findings. First, the concurrent cognitive task caused significantly shorter forward displacement and mediolateral deviation than without it. Second, high stepping was associated with significantly larger body rotation and mediolateral deviation than at comfortable stepping height. Third, the attentional focus on the cognitive task was significantly lower in HStep+CT than in CStep+CT.

Forward displacement and lateral deviation were shorter when performed with the concurrent cognitive task. The cognitive task was also associated with a lower stepping height. This may explain at least in part why the displacements were shorter, especially considering that the mediolateral displacement was significantly shorter at comfortable than at high stepping. An alternative explanation for the effect of this cognitive task on linear body displacement could be that the participants shifted their attention away from the stepping task, which thereby promoted a more unconstrained regulation of rhythmic movements and dynamic postural control.²⁷ More automatic control may have enhanced the consistency of the participants' stepping movements or improved their dynamic postural control by reducing their body sway.

Body rotation and mediolateral displacement were larger at high than at comfortable step height. For body rotation, the difference between the means was larger than the clinically meaningful difference (set at 8°; see "Participants" section) only when we compared CStep+CT with HStep+CT. The difference between CStep and HStep was less than 8°, which indicates that even if there was

a significant main effect of step height on body rotation (unsigned values), and even if the effect size was large, the impact of step height was small in the absence of the cognitive task. Nevertheless, the changes observed in body rotation and mediolateral displacement were likely because it was more challenging to maintain single-leg balance control when the opposite knee was lifted high. The body's centre of mass moves in the frontal plane when making a step,³⁴ and therefore it repeatedly moves mediolaterally during the test.

In high stepping, the associated body sway was likely larger than at comfortable step height, and consequently the mediolateral displacement was more difficult to control. In addition, because the lifted foot was farther from the ground in high stepping, repositioning this foot in the same spot from which it was lifted is less likely than at comfortable step height. If the foot-repositioning error was systematic from step to step and larger in high stepping, its accumulation during repetitive stepping would have produced a larger rotation and displacement at high than at comfortable step height.

Another explanation concerns stepping frequency. It was found to be most consistent at 1.86 steps/second, and its variability increased at lower frequencies.³⁵ Thus, our mean stepping frequency at high stepping (1.58 steps/s) was probably associated with more irregular stepping movements than at comfortable step height (1.67–1.69 steps/s). Together with the possibly larger foot repositioning error, inconsistent stepping movements may have contributed to the larger body rotation and mediolateral displacement at high stepping.

Finally, the greater effort associated with high stepping may have increased the attentional demand of the test. This is revealed by the significantly higher percentage of attention allocated to the stepping task in HStep+CT than in CStep+CT. The participants had to focus on keeping their steps high while simultaneously remaining in the same position. As a result, their attentional capacity was probably exceeded, and their performance was affected; this was proposed by the capacity-sharing theory for information processing.^{29–31}

In summary, our results indicate that a concurrent cognitive task and step height are important elements in the performance of the Fukuda stepping test in healthy young adults. Patients and participants in future research should be instructed to use a comfortable step height during the test. Moreover, clinicians and researchers must know that test performance is improved by a concurrent cognitive task, at least for young adults. However, this may be due to the lower stepping height with the cognitive task than without it.

This study had three main limitations. First, participants' performance on the cognitive task (the counting task) was not measured as a single task during quiet

standing. Thus, we could not establish whether it had been affected during stepping. Second, the trials for each condition were not fully randomized, and there may have been bias caused by the order of the trials. Third, the study power was high enough to detect the important main effects but insufficient to detect interactions between the two within-person factors. This indicates that future studies should have a larger sample size.

CONCLUSION

This study revealed that forward displacement and lateral deviation were significantly shorter when participants performed the Fukuda stepping test with the concurrent cognitive task than without it. In addition, body rotation and lateral deviation were significantly larger at high stepping than at comfortable stepping height. These findings show that healthy young adults who perform the Fukuda stepping test are influenced by these two factors. This new knowledge could improve the specific instructions given to patients and research participants, thereby promoting standardization of the test.

KEY MESSAGES

What is already known on this topic

The Fukuda stepping test is part of the battery of tests used by physiotherapists to assess patients with vestibular disorders and patients with dizziness. Patients step in place with their vision obscured and are instructed to stay in the same spot and not turn. Nevertheless, they do move from the spot and they do turn, thus exhibiting body rotation and linear displacement, mainly forward. This inability to stay on the same spot has also been observed in healthy young individuals.

What this study adds

This study shows that executing a difficult cognitive task during the Fukuda stepping test modifies linear displacement, and stepping with high knees modifies body rotation and mediolateral displacement in healthy young individuals. Patients and research participants should be instructed to use a comfortable step height during the test. Clinicians and researchers must be aware that the test performance may be improved by a concurrent cognitive task, at least among young adults

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