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RESEARCH ARTICLE

Less noise during dual-task walking in healthy young adults: an analysis of different gait variability components

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Abstract

Dual-task costs of gait (variability) parameters are frequently used to probe the grade of automaticity of walking. However, recent studies reported contradicting dual-task costs for different gait variability measures within the same cohorts. The effects of a dual-task on the gait pattern are, thus, not fully understood. The aim of the current study was to analyze the different gait variability components ('Tolerance', 'Noise', and 'Covariation') during dual-task walking compared to single-task walking. In an experimental study, 21 young and healthy adults (11 males, 10 females, age: 24 ± 3 years) were included. The participants completed three experimental conditions: (a) single-task walking, (b) dual-task walking (serial-seven subtractions), and (c) cognitive single task in sitting position. To analyze different gait variability components, we applied a method which distinguishes the three components: 'Tolerance', 'Noise', and 'Covariation' (TNC). To test for differences, we used the statistical parametric mapping method. Compared to single-task walking, the results depict lower gait variability of the result parameters during the dual-task condition at 0–15% ($p = 0.010$) and 94–100% ($p = 0.040$) of the stance phase and 0–63% ($p < 0.001$) during the swing phase. The decreased result parameter variability was due to less (sensorimotor) 'Noise' (stance: 2–100%, $p < 0.001$; swing: 2–59%, $p < 0.001$) during the dual-task walking condition. In further studies, the sources of the reduced unstructured (sensorimotor) noise in the dual-task condition should be analyzed to better understand the effect of a cognitive dual task on the gait pattern.

Keywords Gait · TNC analysis · Functional variability · Covariation · Noise · Uncontrolled manifold

Introduction

The evaluation of gait variability is frequently used to rate sensorimotor control of gait (Hamacher et al. 2011; Hausdorff 2005). Traditionally, high movement variability is interpreted as an indicator of unwanted noise within the sensorimotor system (Davids et al. 2003; Schubert 2013). Furthermore, dual-task costs of gait (variability) parameters are frequently used to probe the grade of automaticity of the walking task. Here, higher-performance decrements during the dual-task condition are usually interpreted as less automaticity (Clark 2015). For example, in a recent study, we compared different gait variability measures during normal overground walking vs. dual-task walking and found a significant increase in stride time variability during the dual-task condition (Hamacher et al. 2019). There are several theories on the underlying mechanism of the motor–cognitive interference that explain this performance loss (Bayot et al. 2018). Accordingly, it is expected that both (dual) tasks (walking and the cognitive task) are competing for resources of executive functions, attention or working memory (Bayot et al. 2018) leading to performance losses in either or both tasks.

Contrary to these findings, the aforementioned study revealed less variability of the minimum toe clearance (MTC) event in the dual-task condition in healthy young and older adults (Hamacher et al. 2019). The MTC describes the local minimum of the toe–ground distance during the mid-swing phase and is considered crucial for maintaining

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stable gait. Similar findings (decreased MTC variability during dual-task walking) were reported for older adults in another study (Santhiranayagam et al. 2015). Improvements in motor performance of highly automated movements due to the inclusion of a secondary (cognitive) task have also been shown for golf putting and soccer dribbling (Beilock et al. 2002; Beilock and Gray 2012). The authors discussed that in skilled movements cognitive tasks might shift the focus of attention away from the movement control which in turn improves movement performance (Beilock et al. 2002; Beilock and Gray 2012). Since the control of a 'healthy' gait pattern is highly automatic (Clark 2015), a dual task could also reduce gait variability.

Taken together, the trade-off of two contrasting effects, (1) competing for resources and (2) altering the focus of attention, differently influences walking performance. This has already been repeatedly discussed for gait variability measures (Decker et al. 2016; Hamacher et al. 2019; Lövdén et al. 2008). However, those papers implicitly assume that reduced gait variability indicates improved sensorimotor control. Nowadays, it is well accepted that movement variability is not only a nuisance ("bad" aspect of variability, Sternad 2018) but also a consequence of adapting to environmental changes or compensating for internal or external perturbations ("good" aspect of movement variability, Loosch 1999). The latter variability components have been termed "functional variability" (Hamacher et al. 2017; Hamacher and Zech 2018; Müller and Loosch 1999). Thus, increased movement variability might indicate improved (functional variability) or worsened movement control (variability as a nuisance). To interpret movement variability as "bad" or "good", the different components of movement variability should be considered.

To analyze those different components of movement variability, methods, such as the TNC analysis ('Tolerance', 'Noise', 'Covariation'; Müller and Sternad 2003, 2004, 2009), were developed. Those methods are based on Bernstein's problem (Bernstein 1967) considering that, due to redundancy within the motor system, the movement result (e.g., hitting bullseye in a dart-throwing task, Müller and Sternad 2009) can be perfectly reached by different sets of execution parameters (e.g., dart angle and speed at the release event, Müller and Sternad 2009).

To summarize, it is still speculative why an increasing body of literature report beneficial effects of dual-task walking conditions (compared to single-task walking) on different gait variability parameters (Decker et al. 2016; Hamacher et al. 2019; Lövdén et al. 2008). The TNC method is a promising approach to examine different parameters of sensorimotor control during gait and may help to understand the dual-task effects on walking abilities. Therefore, in this study, we analyze the different (TNC) components of gait variability during dual-task walking. Such knowledge is not only needed to better understand motor control. It is also relevant, as the MTC variability is a critical event with higher MTC variability increasing the likelihood of tripping and, thus, of falls (Barrett et al. 2010).

Based on the current body of literature (Decker et al. 2016; Hamacher et al. 2019; Lövdén et al. 2008), we hypothesize that compared to normal single-task walking, a cognitive dual task reduces the gait variability in the result parameters in young healthy adults. In agreement with previous studies, the MTC (Barrett et al. 1991; Hamacher et al. 2014, 2017) as well as the control of the center of mass (CoM) (Papi et al. 2015; Qu 2012; Tawy et al. 2018) were used as task-relevant parameters. We further aimed to analyze which gait variability component ('Tolerance', 'Noise', 'Covariation' of the TNC analysis) causes the anticipated reduction of the results' parameters variability.

Methods

Study design

In an experimental study, the effect of a cognitive dual task on different components of gait variability was analyzed. Using a within-subjects design, all participants completed three conditions in randomized and balanced order: (a) single-task walking, (b) dual-task walking with a secondary cognitive task, and (c) a cognitive single task in a sitting position.

Participants

We recruited 21 young and healthy adults (11 males, 10 females, age: 24 ± 3 years, weight: 73 ± 15 kg, height: 1.75 ± 0.11 m). All participants were sports science students and recruited by means of announcements during the courses. The inclusion criterion was an age between 18 and 30 years. Any self-reported motor-functional impairments that could affect gait led to exclusion. Recruitment and data collection lasted from May to June 2018. All participants provided their written informed consent after they were briefed about the research protocol which complied with the principles of the Declaration of Helsinki and was approved by the Ethical Commission of the Faculty of Social and Behavioral Sciences, Friedrich Schiller University of Jena (no. FSV 18/11).

Testing procedure

To analyze the effect of a cognitive dual task, all participants walked on a treadmill (Fa. Bertec Corporation, Columbus, USA) which was installed at ground level. Their preferred walking speed was registered using a step protocol (Dal et al.

2010). Thereto, the participants walked at a speed of 0.8 m/s. However, the participants were not informed about the walking speed at any time. The speed was increased by 0.1 m/s every 15 s until the individual comfortable walking speed was reached. Thereafter, the last determined individual comfortable walking speed was increased by 0.3 m/s and then reduced by 0.1 m/s every 15 s until the participants notified us again that the comfortable walking speed was reached. We repeated this procedure three times and used the mean of the repetitions as the preferred walking speed in all subsequent walking conditions.

Thereafter, the participants completed three conditions in randomized and balanced order: (a) single-task walking, (b) dual-task walking with a secondary cognitive task (serial-seven subtraction starting from a random three-digit number between 700 and 800), and (c) the cognitive single task in a sitting position. The participants' voices were recorded using a digital recorder (DVT4000, Koninklijke Philips N.V., the Netherlands) to rate the performance of the cognitive task during post-processing. Each condition lasted 3.5 min.

To register gait kinematics, we used a measurement system with ten infrared cameras (Opus 700+, Qualysis AB, Goteborg, Sweden). The system was calibrated on each test day. Passive retro-reflective markers (diameter: 12.5 mm, Qualysis AB, Goteborg, Sweden) were attached to the participants' skin using a common marker set (gait IOR, Leardini et al. 2007). During walking, we tracked the marker positions at 150 Hz and recorded the data by means of the QTM software (version 2.17, Qualisys AB, Göteborg, Sweden). Data recording was started after the participants were walking with their preferred walking speed for about 10 s.

Data analysis

Since we used the TNC method in our study, we reason our choice of result and execution parameters as a prerequisite for applying the TNC method. During stance phase, the control of the center of mass (CoM) has been considered a task-relevant result parameter and the individual joint kinematics parameters of the execution space (Papi et al. 2015; Qu 2012; Tawy et al. 2018). During the swing phase, the MTC is considered a task-relevant parameter (Barrett et al. 1991; Hamacher et al. 2014, 2017) which obviously is affected by the pelvis position and the joint kinematics (hip, knee, and ankle joint angles).

Since different variability components should be analyzed, the non-filtered data sets were exported to Visual3D (C-Motion, version 6). A virtual toe maker was defined as the projection of the toe marker (first metatarsal heads) onto the ground at the normal upright stance and tracked relative to the foot segment. Thereafter, the joint (ankle, knee, hip), CoM and toe positions, as well as the foot's angular velocity (the segments angular velocity that is calculated in Visual 3D by default) of the sagittal plane, were exported as text files. The subsequent analysis was conducted with self-made Matlab® scripts. Gait events (heel contact, toe off) were identified based on the foot's angular velocity data in the sagittal plane (Sabatini et al. 2005). For the secondary analysis, the individual MTC event was defined as the local minimum of toe clearance (toe–ground distance) during the swing phase. MTC variability was calculated as the standard deviation across the MTC events for each participant, separately. The CoM position was approximated as the interception diagonals fitted to the anterior and posterior superior iliac spines (Papi et al. 2015). Thereafter, the gait kinematics was time normalized to 101 samples for stance and swing phase, separately. For each participant and stride, the frontal and sagittal plane angles (angles within the laboratory coordinate system; the axis corresponding to the walking direction and the vertical axis define the sagittal plane) of the ankle, knee and hip joints, as well as the foot–ground angles, were calculated based on the time-normalized data. Furthermore, for each participant, the means of the segment lengths (foot, shank, thigh) across all strides were computed.

We applied the TNC method as described by Müller and Sternad (2003, 2004) to analyze the different components of gait variability. The analysis was restricted to the kinematics of the right leg. Here, the effects of the execution parameters on the result parameters are modeled. As already reasoned, we used the (approximated) CoM as the result parameter during stance. The frontal and sagittal plane angles (foot–ground, ankle, knee and hip angles) were considered execution parameters (Fig. 1). During the swing phase, the toe–ground distance (toe clearance) was the result parameter and the frontal and sagittal plane angles of the hip, knee, and ankle joint as well as the height of the approximated CoM (reflecting the overall effect of the stance leg) are considered execution parameters.

The original TNC method (as described in Müller and Sternad 2003, 2004) distinguishes three variability components 'Tolerance', 'Noise', and 'Covariation' by comparing two distinct conditions: in our study the conditions normal walking vs. dual-task walking. 'Tolerance' registers the sensitivity of different sets of execution parameters (e.g., different means of the hip, knee and ankle angle at a certain time of the gait cycle) for noise. 'Noise' gathers the amount of unstructured noise in the execution space. 'Covariation' rates the covariation within execution parameters (Müller and Sternad 2009). We will briefly describe the calculation process according to Müller and Sternad (2004). Using our model (Fig. 1), the result parameter values were calculated as a function of the execution parameters. As a criterion to rate the performance P, the gait variability of the result parameter (CoM during stance phase, toe–ground distance during swing phase) was calculated as the standard deviation across all strides. This was done for single-task walking

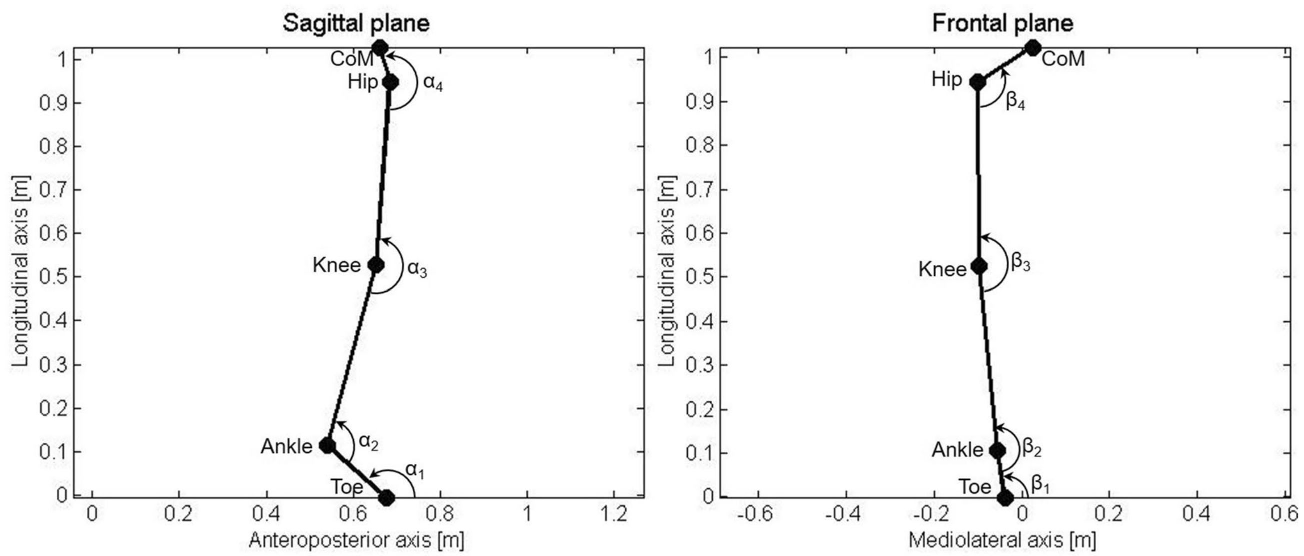

Fig. 1 Model of the right leg in the sagittal (left) and frontal (right) plane. This model was used to analyze the effect of the elementary parameters on the result parameters using the TNC method

$P(A)$ and dual-task walking $P(B)$. We will call the set of execution parameters A and B for single-task walking and dual-task walking, respectively. To assess the effect of covariation within the execution parameters, all covariation within the execution parameters was removed by permuting the execution parameter values for single-task and dual-task walking, separately. We refer to the permuted sets of execution parameters as A_0 and B_0. Then, the result parameter was recalculated using our model (Fig. 1). For the swing phase, those theoretically calculated toe–ground distances (as the result parameters) in A_0 and B_0 might be negative. To limit the chance effect of the particular permutation on the result parameter, the permutation and recalculation process was repeated 100 times. Thereafter, the performance was rated again and we will refer to it as $P(A_0)$ and $P(B_0)$ for single-task and dual-task walking, respectively. To be able to rate the sensitivity of a set of execution parameters (e.g., mean joint angles during single-task vs. dual-task walking), the means of both sets of execution parameters were calculated for single-task walking (A) and dual-task walking (B). The differences between the means were added to the execution parameters A_0 to receive the new shifted set of execution parameters $A_{0,\text{shift}}$. $A_{0,\text{shift}}$ is based on A_0, depicts no covariation and has the same mean of the execution parameter values as B. We then recalculated the performance parameter $P(A_{0,\text{shift}})$. According to Müller and Sternad (2004) the differences in 'tolerance', 'noise' and 'covariation' are calculated as: $\Delta\text{tolerance} = P(A_{0,\text{shift}}) - P(A_0)$, $\Delta\text{noise} = P(B_0) - P(A_{0,\text{shift}})$ and $\Delta\text{covariation} = P(B) - P(B_0) + P(A_0) - P(A)$. The calculation was repeated for each participant and time-normalized data point. For all variability components, a positive value indicates increased result parameter variability (decreased performance) during the dual-task condition compared to the single-task condition. Thus, a positive 'Tolerance' value decreases the result parameter performance in the dual-task condition. This would be interpreted as increased sensitivity to perturbations of the set of execution parameters in the dual-task condition. A positive 'noise' value is the result of more (sensorimotor) noise in the dual-task condition. A positive 'covariation' value indicates an increase in the result parameter variability in the dual-task condition due to less covariation within the execution space.

To rate the cognitive performance, the correct serial-seven subtractions were identified and normalized to the number of correct subtractions per minute.

Statistics

To analyze time-continuous data over the entire gait cycle, we applied the statistical parametric mapping analysis. We used the open-source package 'spm1D' (version 0.4.5, Pataky 2012) which was developed to statistically analyze one-dimensional biomechanical (registered) curves (Pataky 2012). The SPM analysis uses the random field theory to account for temporal correlations within each data set and to avoid the problem of multiple testing. To show if the variability of the result parameters differs in dual-task vs. single-task walking (to test our hypothesis), the data were compared using the repeated measures t test version of the SPM method. Since the TNC method already compares two distinct conditions (e.g. single task vs. dual task), the significance of each of the time-continuous variability components ('Tolerance', 'Noise', and 'Covariation') was assessed using the one-sample t test version of the SPM package, testing for differences compared with the value 'zero'.

In a secondary analysis, differences of the MTC variability events and the cognitive performance during single- vs. dual-task walking were assessed with paired-sample t tests (JASP, version: 0.9.2, University of Amsterdam, The Netherlands).

Results

In average, 195 (SD: 10) and 194 strides (SD: 10) were analyzed for normal and dual-task walking, respectively.

The result parameter depicted lower variability during the dual-task condition at 0–15% ($p = 0.010$) and 94–100% ($p = 0.040$) of the stance phase and 0–63% ($p < 0.001$) during the swing phase (Fig. 2).

Figure 3 shows a significant effect of 'Tolerance' during the stance phase (3–73%, $p < 0.001$) increasing the variability of the CoM height in the dual-task condition. No such effect was found during the swing phase. Compared to single-task walking, the dual-task condition produced significantly less 'Noise' (stance: 2–100%, $p < 0.001$; swing: 2–59%, $p < 0.001$) indicating a better performance (decreased variability) of the result parameters. On the contrary, decreased result parameter performance (increased variability) during the dual-task condition was registered due to the component 'Covariation' (stance: 28–41%, $p < 0.001$, 43–44%, $p = 0.046$, 46–47%, $p = 0.048$, 85–100%, $p < 0.001$; swing 12–17%, $p = 0.039$, 51%, $p = 0.049$). This indicated less covariation within the execution parameters during dual-task walking compared to the single-task walking condition.

The MTC event was registered at 59% (SD: 2%) of the swing phase for both single-task and dual-task walking. The MTC variability was reduced during the dual-task condition ($p < 0.001$, $d = 1.31$, Table 1) but there was no effect on the cognitive performance ($p = 0.250$, $d = 0.26$, Fig. 4, Table 1).

Discussion

The aim of the current study was to analyze if a cognitive dual task reduces gait variability in healthy young adults. Furthermore, we wanted to identify which components of gait variability cause a reduction in the result parameters'

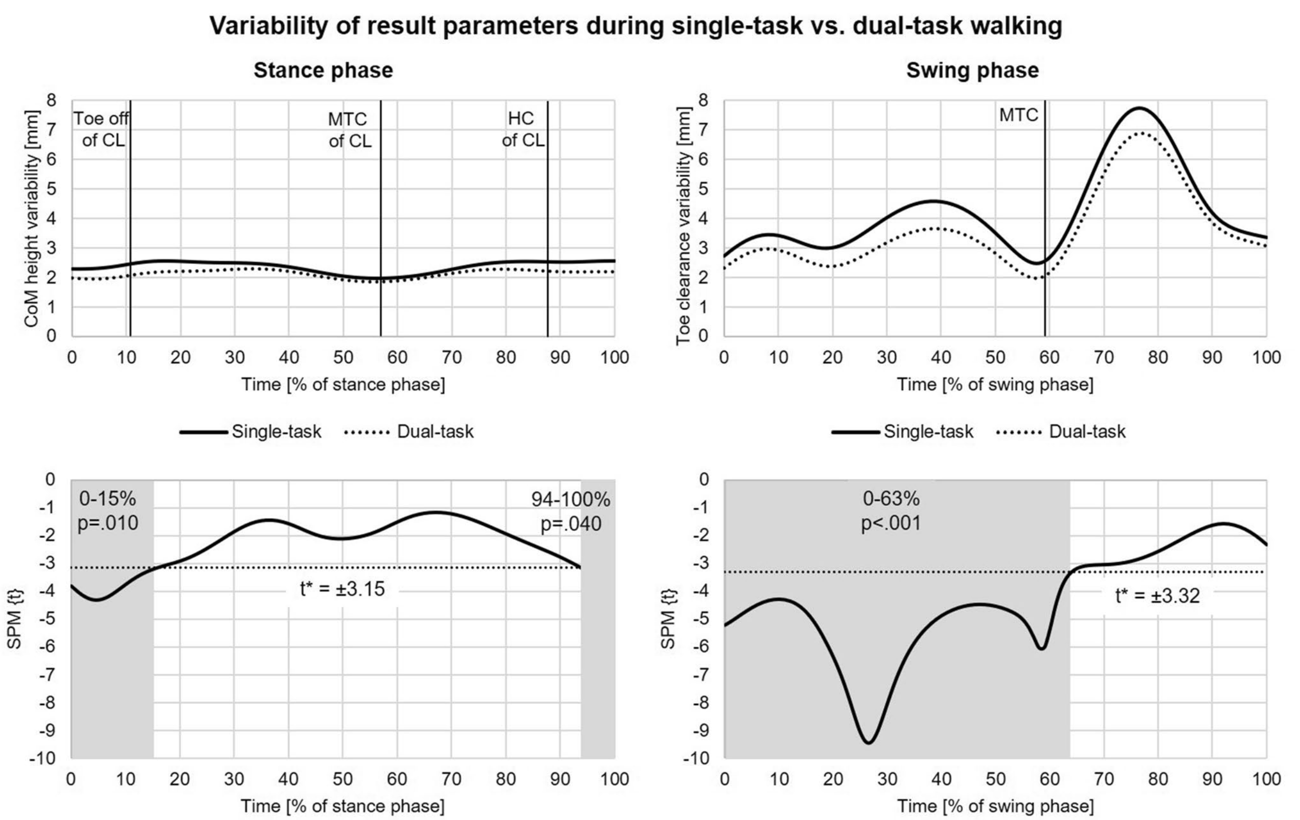

Fig. 2 Effect of dual-task walking (compared to single-task walking) on the result parameters: center of mass (CoM) height variability for stance phase (left) and minimum toe clearance (MTC) variability for swing phase (right). Differences were statistically assessed using the statistical parameter mapping method (two-sided, paired t test versions)

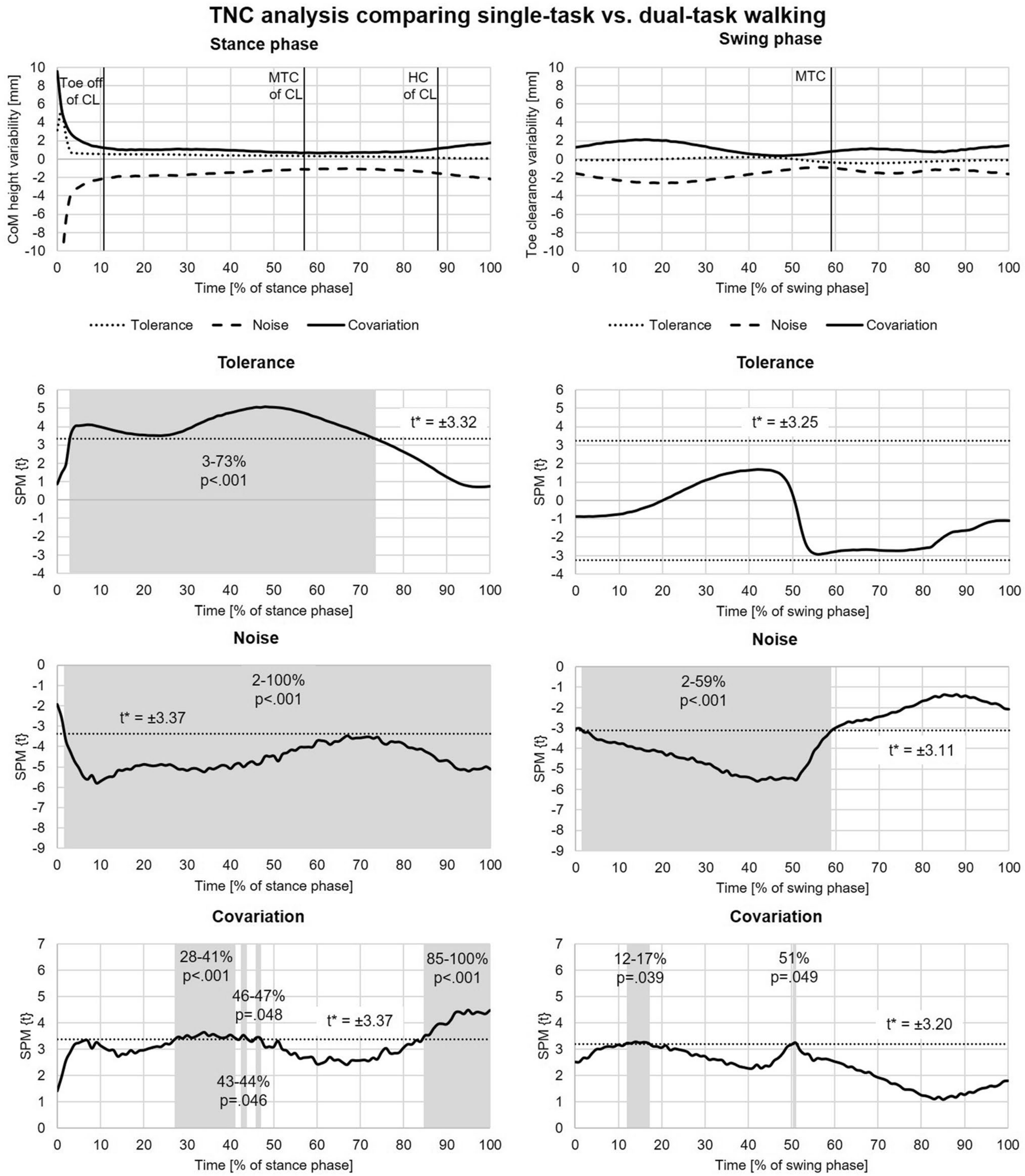

Fig. 3 Results of the TNC analysis comparing dual-task walking with single-task walking for stance phase (left) and swing phase (right), separately. Since the TNC analysis compares two distinct test conditions (e.g., dual-task vs. single-task walking), differences were statistically assessed using the one-sample *t* test versions (two-sided) of the statistical parameter mapping approach

variability. Therefore, the different variability components were calculated using the TNC method.

Compared to single-task walking, in agreement with our hypothesis, we found reduced variability of the result parameters (CoM height in stance; toe clearance in swing) in the dual-task condition. This was caused by reduced noise within the execution parameters during the dual-task condition. Our results corroborate with another study by

Table 1 Gait, gait variability and cognition measures during single-task walking vs. dual-task walking

	Single task Mean (SD)	Dual task Mean (SD)	t (df = 20)	p	Cohen's d
Gait parameters					
ICWS (m/s)	1.3 (0.2)				
Stride time (s)	1.06 (0.07)	1.06 (0.06)	1.78	0.090	0.39
MTC (mm)	11.5 (4.2)	10.7 (4.2)	2.39	0.027	0.52
Gait variability parameters					
Stride time variability (ms)	15.2 (5.7)	13.6 (3.8)	1.55	0.138	0.34
MTC variability (mm)	2.4 (0.6)	2.0 (0.5)	6.00	< 0.001	1.31
Cognition					
Correct responses (*n*/min)	17.0 (6.3)	16.1 (6.9)	1.18	0.250	0.26

ICWS individual comfortable walking speed, *MTC* minimum toe clearance

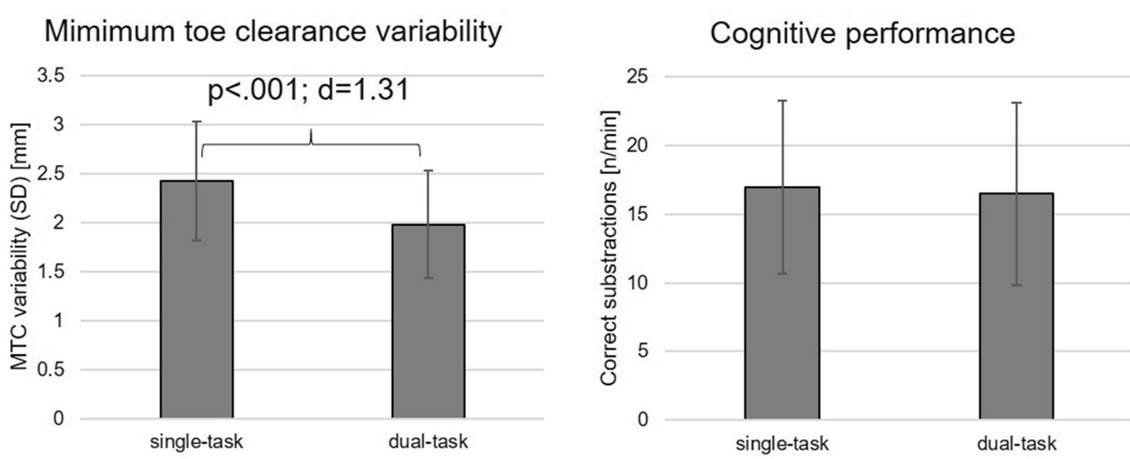

Fig. 4 The effect of a cognitive dual task on the variability of the minimum toe clearance event (left) and on the cognitive task (serial-seven subtractions, right)

Hamacher et al. (2019). Here, a reduced MTC variability during normal overground walking in healthy young and older adults was reported. Likewise, Santhiranayagam et al. (2015) revealed a reduced MTC variability in the dual-task condition (carrying a glass of water) during treadmill walking but only in older adults and only while they were walking with their preferred walking speed in each test condition. In our current study, the participants walked on a treadmill with the same speed during both conditions. Reduced gait variability of other temporospatial parameters during dual-task walking was also reported in other studies (Decker et al. 2016; Lövdén et al. 2008).

Besides the analysis of the MTC event, we also rated different variability components to explain the improved (decreased) result parameter variability during dual-task walking. According to our results, the reduced variability of the result parameters is due to reduced noise within the execution space. According to a current review, noise is generated at all levels of the sensorimotor system. For example, there are sources of sensory noise (e.g., transducer noise), sources of cellular noise (e.g., membrane potential fluctuations) and sources of motor noise (e.g., Ca^{2+}-channel noise, Faisal et al. 2008). Furthermore, noise can accumulate in neuronal networks (Faisal et al. 2008). Based on the results of our current study, it is impossible to pin down the exact reason for the reduced noise during the dual-task condition. While we can only speculate on possible reasons, to the best of our knowledge, this remains the first study showing reduced noise within the sensorimotor system during dual-task walking.

The effect of reduced gait variability during dual-task walking was discussed several times (Decker et al. 2016; Hamacher et al. 2019; Lövdén et al. 2008). It is well known that skill-focused attention can impair movement performance in well-learned (highly automatic) movements. For example, this has been shown for golf putting or dribbling in soccer players (Beilock et al. 2002; Beilock and Gray 2012). The control of a 'healthy' gait pattern in younger and healthy older adults is highly automatic (Clark 2015), and during the gait analysis (at least in our study) the participants knew that their gait pattern would be analyzed. Thus, the participants might shift their attention to their movement which could have disrupted the performance. If so, during the dual-task condition, there is probably no skill-focused attention improving movement performance during dual-task walking. This has also been shown for putting and dribbling (Beilock et al. 2002) and was discussed for reduced gait variability during dual tasking (Decker et al. 2016; Hamacher et al. 2019; Lövdén et al. 2008). This would explain the improved result parameter performance during the dual-task condition in our current study. Since the result of our current study shows that the reduced gait variability is caused by less sensorimotor noise, the cognitive control (online step-by-step monitoring) of movements might somehow induce unstructured noise into the execution space. However, this remains speculation and needs further research.

Furthermore, we found less covariation within the execution space during the dual-task condition compared to the single-task condition. However, the negative effects of the reduced covariation or the higher sensitivity of the set of execution parameters (of the posture) to perturbations (negative effect of 'Tolerance') during the stance phase were lower than the positive effect of the less noise in the dual-task condition. The component 'Covariation' is, at least partly, coupled with the aspect 'Noise'. According to the minimal intervention principle (Todorov and Jordan 2002), the interplay of unstructured noise and movement control processes would predominantly induce variation in the task-irrelevant direction of the execution space. This would increase the amount of calculated 'Covariation' in our study. Conversely, less noise would also reduce the amount of 'Covariation'.

Our results are not generalizable to an older cohort. If our interpretation approach on gait automaticity adds up, the results could be quite different for participants walking with less automaticity, e.g., in old or impaired adults (for factors affecting gait automaticity see Clark 2015). Furthermore, the results of the TNC analysis depend on the chosen coordinate frame (Müller et al. 2007). However, this is a "shortcoming" of many kinematic analyses. It should also be noted that we did not control for possible cueing effects (e.g., due to the dual task) in this study. However, since we did not detect a significant change in stride time variability, we assume cueing might not have affected our results.

To summarize, we found a reduced variability of the result parameters in the dual-task condition compared to single-task walking in our young and healthy participants. This was caused by reduced (sensorimotor) noise during the dual-task condition. In further studies, the sources of the (reduced) sensorimotor noise should be analyzed.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All participants provided their written informed consent after they were briefed about the research protocol which complied with the principles of the Declaration of Helsinki and was approved by Ethical Commission of the Faculty of Social and Behavioral Sciences, Friedrich Schiller University of Jena (No. FSV 18/11).

References

Barrett DS, Cobb AG, Bentley G (1991) Joint proprioception in normal, osteoarthritic and replaced knees. J Bone Jt Surg 73-B:53–56

Barrett RS, Mills PM, Begg RK (2010) A systematic review of the effect of ageing and falls history on minimum foot clearance characteristics during level walking. Gait Posture 32:429–435. https://doi.org/10.1016/j.gaitpost.2010.07.010

Bayot M, Dujardin K, Tard C, Defebvre L, Bonnet CT, Allart E, Delval A (2018) The interaction between cognition and motor control: a theoretical framework for dual-task interference effects on posture, gait initiation, gait and turning. Neurophysiol Clin 48:361–375. https://doi.org/10.1016/j.neucli.2018.10.003

Beilock SL, Gray R (2012) From attentional control to attentional spillover: a skill-level investigation of attention, movement, and performance outcomes. Hum Mov Sci 31:1473–1499. https://doi.org/10.1016/j.humov.2012.02.014

Beilock SL, Carr TH, MacMahon C, Starkes JL (2002) When paying attention becomes counterproductive: impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. J Exp Psychol Appl 8:6–16. https://doi.org/10.1037//1076-898X.8.1.6

Bernstein N (1967) The co-ordination and regulation of movements. Pergamon Press, Oxford

Clark DJ (2015) Automaticity of walking: functional significance, mechanisms, measurement and rehabilitation strategies. Front Hum Neurosci. https://doi.org/10.3389/fnhum.2015.00246

Dal U, Erdogan T, Resitoglu B, Beydagi H (2010) Determination of preferred walking speed on treadmill may lead to high oxygen cost on treadmill walking. Gait Posture 31:366–369. https://doi.org/10.1016/j.gaitpost.2010.01.006

Davids K, Glazier P, Araújo D, Bartlett R (2003) Movement systems as dynamical systems. Sports Med 33:245–260. https://doi.org/10.2165/00007256-200333040-00001

Decker LM, Cignetti F, Hunt N, Potter JF, Stergiou N, Studenski SA (2016) Effects of aging on the relationship between cognitive demand and step variability during dual-task walking. Age (Dordr) 38:363–375. https://doi.org/10.1007/s11357-016-9941-y

Faisal AA, Selen LPJ, Wolpert DM (2008) Noise in the nervous system. Nat Rev Neurosci 9:292–303. https://doi.org/10.1038/nrn2258

Hamacher D, Zech A (2018) Development of functional variability during the motor learning process of a complex cyclic movement. J Biomech 77:124–130. https://doi.org/10.1016/j.jbiomech.2018.07.015

Hamacher D, Singh NB, Van Dieën JH, Heller MO, Taylor WR (2011) Kinematic measures for assessing gait stability in elderly individuals: a systematic review. J R Soc Interface 8:1682–1698. https://doi.org/10.1098/rsif.2011.0416

Hamacher D, Hamacher D, Schega L (2014) Towards the importance of minimum toe clearance in level ground walking in a healthy elderly population. Gait Posture 40:727–729. https://doi.org/10.1016/j.gaitpost.2014.07.016

Hamacher D, Hamacher D, Müller R, Schega L, Zech A (2017) Exploring phase dependent functional gait variability. Hum Mov Sci 52:191–196. https://doi.org/10.1016/j.humov.2017.02.006

Hamacher D, Hamacher D, Müller R, Schega L, Zech A (2019) The effect of a cognitive dual task on the control of minimum toe clearance while walking. Motor Control. https://doi.org/10.1123/mc.2018-0006

Hausdorff JM (2005) Gait variability: methods, modeling and meaning. J Neuroeng Rehabil 2:19. https://doi.org/10.1186/1743-0003-2-19

Leardini A, Sawacha Z, Paolini G, Ingrosso S, Nativo R, Benedetti MG (2007) A new anatomically based protocol for gait analysis in children. Gait Posture 26:560–571. https://doi.org/10.1016/j.gaitpost.2006.12.018

Loosch E (1999) Allgemeine Bewegungslehre. UTB für Wissenschaft, vol 2100. Limpert, Wiebelsheim

Lövdén M, Schaefer RS, Pohlmeyer AE, Lindenberger U (2008) Walking variability and working-memory load in aging: a dual-process account relating cognitive control to motor control performance. J Gerontol Psychol Sci 63B:121–128

Müller H, Loosch E (1999) Functional variability and an equifinal path of movement during targeted throwing. J Hum Mov Stud 36:103–126

Müller H, Sternad D (2003) A randomization method for the calculation of covariation in multiple nonlinear relations: illustrated with the example of goal-directed movements. Biol Cybern 89:22–33. https://doi.org/10.1007/s00422-003-0399-5

Müller H, Sternad D (2004) Decomposition of variability in the execution of goal-oriented tasks: three components of skill improvement. J Exp Psychol Hum Percept Perform 30:212–233. https://doi.org/10.1037/0096-1523.30.1.212

Müller H, Sternad D (2009) Motor learning: changes in the structure of variability in a redundant task. In: Sternad D (ed) Progress in motor control, vol 629. Springer, Boston, pp 439–456

Müller H, Frank TD, Sternad D (2007) Variability, covariation, and invariance with respect to coordinate systems in motor control: reply to Smeets and Louw (2007). J Exp Psychol Hum Percept Perform 33:250–255. https://doi.org/10.1037/0096-1523.33.1.250

Papi E, Rowe PJ, Pomeroy VM (2015) Analysis of gait within the uncontrolled manifold hypothesis: stabilisation of the centre of mass during gait. J Biomech 48:324–331. https://doi.org/10.1016/j.jbiomech.2014.11.024

Pataky TC (2012) One-dimensional statistical parametric mapping in Python. Comput Methods Biomech Biomed Eng 15:295–301. https://doi.org/10.1080/10255842.2010.527837

Qu X (2012) Uncontrolled manifold analysis of gait variability: effects of load carriage and fatigue. Gait Posture 36:325–329. https://doi.org/10.1016/j.gaitpost.2012.03.004

Sabatini AM, Martelloni C, Scapellato S, Cavallo F (2005) Assessment of walking features from foot inertial sensing. IEEE Trans Biomed Eng 52:486–494. https://doi.org/10.1109/TBME.2004.840727

Santhiranayagam BK, Lai DTH, Sparrow WA, Begg RK (2015) Minimum toe clearance events in divided attention treadmill walking in older and young adults: a cross-sectional study. J Neuroeng Rehabil 12:240. https://doi.org/10.1186/s12984-015-0052-2

Schubert P (2013) Die Anwendung nichtlinearer Verfahren zur Charakterisierung der menschlichen Variabilität aus Zeitreihen. Deutsche Zeitschrift für Sportmedizin 64:132–140. https://doi.org/10.5960/dzsm.2012.064

Sternad D (2018) It's not (only) the mean that matters: variability, noise and exploration in skill learning. Curr Opin Behav Sci 20:183–195. https://doi.org/10.1016/j.cobeha.2018.01.004

Tawy GF, Rowe P, Biant L (2018) Gait variability and motor control in patients with knee osteoarthritis as measured by the uncontrolled manifold technique. Gait Posture 59:272–277. https://doi.org/10.1016/j.gaitpost.2017.08.015

Todorov E, Jordan MI (2002) Optimal feedback control as a theory of motor coordination. Nat Neurosci 5:1226–1235. https://doi.org/10.1038/nn963