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“The influence of auditory stimulation on whole body variability in healthy older adults during gait”

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ABSTRACT

Acoustic stimulation appears to be a promising strategy in reducing the risk of falling in older adults, demonstrating effectiveness in improving stability. However, its impact on movement variability, another crucial indicator of fall risk, seems to be limited. This study aims to assess movement variability during walking in a cohort of healthy older adults exposed to three different frequencies of acoustic stimulation (90%, 100% and 110% of each subject’s average cadence). Using a systemic approach based on network theory, which considers the intricate relationships between all body segments, we constructed connectivity matrices composed of nodes, represented by bony landmarks, and edges, consisting of the standardised covariance of accelerations between each pair of nodes. By introducing a new metric called Similarity Score (S-score), we quantified the ability of each individual to repeat the same motor pattern at each gait cycle under different experimental conditions. The study revealed that rhythmic auditory stimulation (RAS) at 100% and 90% of the mean cadence significantly increased the S-scores compared to the baseline. These results highlight the effects of RAS in increasing gait repeatability in healthy older adults, with a focus on global kinematics.

1. Introduction

Ageing is a physiological process that involves progressive motor and cognitive changes. The alteration of the motor system is caused by the combination of numerous factors, including loss of muscle mass, reduction in flexibility, changes in sensory perception, impairment of the postural and motor control systems and reaction times (Woollacott et al., 1986). This results in impaired balance and variability of movement, increasing the risk of falling, with repercussions on the functionality and autonomy (Lage et al., 2022).

Researchers have explored strategies that can help enhance motor control and reduce the risk of falling in the older adults (Khanuja et al., 2018; Sherrington et al., 2020). The rhythmic auditory stimulation (RAS), which involves the use of metronome or music, has been shown to improve static and dynamic stability and movement patterns in physiological and pathological conditions (Ashoori et al., 2015; Hayden et al., 2009). In our previous work we found that a RAS based on the average cadence of older adults improves dynamic stability (Minino et al., 2021; Troisi Lopez et al., 2021). In particular, they showed that a RAS frequency equal to or 10 % higher than the average cadence of an individual was able to increase stability. Wittwer et al. (2013) also analysed the effect of the RAS on gait in healthy older adults, finding that acoustic stimulus had an effect on spatiotemporal parameters, and in particular an increase in cadence, mean stride time, and double support time, although there were no significant results regarding movement variability (Wittwer et al., 2013). This result is in agreement with Baker et al. (2010), who reported a reduced gait variability in patients with Parkinson’s disease but not in healthy controls (Baker et al., 2008). It is important to emphasise that variability is not only considered a negative aspect, given that it is fundamental in locomotion for adaptation to external conditions that require motor readjustment. Some studies have examined the adaptability of gait to complex and

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variable sensory (visual or auditory) stimuli (e.g., based on fractal dynamics). Vaz et al. (2020), demonstrated that when elderly people are exposed to visual or auditory stimuli characterised by fractal-like variability, their gait shows an increase in complexity and adaptability (Vaz et al., 2020a). Nevertheless, it is also known that ageing entails a significant increase in variability caused by reduced motor control, and that may lead to an increase in instability(Callisaya et al., 2010; Kang & Dingwell, 2008).

To date, to the best of our knowledge, there has been no evidence of changes in gait variability due to RAS in healthy individuals, including the older adults. However, many studies examining the impact of RAS (with fixed rhythm) on movement variability have primarily focused on assessing spatiotemporal parameters. The spatiotemporal parameters are the most common variables used to evaluate the gait both in physiological and in pathological conditions(Arellano-González et al., 2020; Roberts et al., 2017). They are easy to calculate, provide valuable information on gait-specific characteristics and are useful to assess walking abilities in both healthy people and those with motor disabilities. However, they come with some limitations. While these parameters offer a summarised representation of walking outcomes, they cannot elucidate the intricate kinematic interactions underlying gait. Functioning as post-hoc measures, they provide information that is specific to the external manifestations of walking characteristics, but they offer limited insight regarding the whole-body kinematic interactions that define gait. Furthermore, the predominant focus of spatiotemporal parameters on lower limb movements restricts their ability to fully encapsulate the holistic nature of human locomotion. Complex movements, as the gait, require to accurately coordinate different body segments, making every part of the body relevant to the extent that it relates to all the others, and not as a separate element (Bernstein, 1966). Hence dismissing the evaluation of the interaction between body parts may lead to information loss and, consequently, the inability to observe the actual effects of RAS on the kinematics at whole-body level. In fact, we hypothesise that RAS, rather than producing limited and circumscribed improvements, exerts a systemic influence on the entire motor network. This means that the effect of stimulation is not limited to individual components of the motor system, but rather it affects the spatiotemporal interactions involving the entire motor system.

For this reason, we believe it is useful to evaluate the effect of RAS on gait through a multidimensional approach that systematically considers the multiple interactions occurring between all parts of the body.

An already widely used approach in studying the relationships that take place between elements within a complex system is network analysis (Romano et al., 2024). Although network theory is still an under-explored approach in motion analysis, recent studies have applied it to the study of human movement. Specifically, network theory has been used as a framework to study human movement and coordination, in particular during gait. To this regard, we recently developed the kinectome which analyses the pairwise interactions among body segments during movement (Troisi Lopez et al., 2022). The kinectome is a correlation matrix where the nodes represent body segments (i.e., bone landmarks) and the edges are defined as the standardised covariance of the time series describing the trajectories (or their derivatives) between each pair of them. In this way, we can assess each part of the body individually, not as an independent element, but rather in terms of its way of communicating with all the other parts. The kinectome can therefore be a useful method to study movement in a whole-body perspective, providing a methodological framework that fits well with our purpose. Furthermore, in such a study, it was shown that kinectomes based on jerk data were the ones showing the greatest ability to differentiate gait patterns from different participants, with respect to other vector quantities. Within this framework, we borrowed from studies employing test–retest matrices to measure the stability of the patterns within them (Amico & Goñi, 2018), extracting a parameter that we named Similarity Score (S-Score). Specifically, this parameter quantifies the similarity between two kinectomes created upon different recordings of the same task, taking into consideration the movement pattern expressed by the whole body, including the interactions among all parts of the body. As a result, high S-Score would correspond to low test–retest repeatability between trials of the same motor task.

Hypothesising that RAS may reduce variability of gait when we look at the whole-body kinematics, we assessed repeatability, as a preliminary proxy of variability, based on the kinematic network of thirteen healthy older adults subjected to acoustic rhythmic stimuli. Specifically, we administered three different stimuli based on each individuals' natural cadence (equal to it, +10 %, and −10 %), and used test–retest kinectome matrices of the respective trials to calculate the S-Score and assess the repeatability of gait. Finally, to get a comprehensive view of the motor characteristics of our sample, we examined each condition by assessing spatiotemporal parameters (such as step length, step width, etc.), and their variability through the measurement of the coefficient of variation (CV), a widely employed metric for evaluating variability.

2. Materials and methods

2.1. Participants

Thirteen older adults, aged between 65 and 85 years old were recruited for this study. Inclusion criteria were as follows: (1) Mini-Mental State Examination $>$ 24 (Folstein et al., 1975); (2) Frontal Assessment Battery $>$ 12 (Dubois et al., 2000); Beck Depression Inventory II $<$ 13 (Beck et al., 1996); no neurological or psychiatric disorders, and no motor or hearing disorder. The participants signed an informed consent in accordance with the declaration of Helsinki. The study was approved by the Asl Napoli 1 Centro Ethic Committee (protocol number: 250-N. Reg. 17–2023 oss).

2.2. Stereophotogrammetric acquisition

The acquisitions were conducted at the Motion Analysis Laboratory of the University of Naples "Parthenope". Gait data was collected using a motion analysis system consisting of eight infrared cameras (ProReflex Unit—Qualisys Inc., Gothenburg, Sweden). These cameras recorded the light reflected by 55 passive markers placed on the participants' anatomical landmarks of the whole body, in accordance with the modified Davis protocol(Davis et al., 1991). The participants were instructed to walk in a straight path 10 m long at their preferred speed. Subsequently, the average cadence of each participant was calculated, and they were asked to walk at the pace of different acoustic stimuli, based on the average cadence. Specifically, participants walked at three different stimulation frequencies: 100 %, 90 % and 110 % of their own mean cadence (Minino et al., 2021; Yu et al., 2015). The metronome (MA-1 Solo Metronome, Korg—UK) emitted the RAS, generating an acoustic stimulation at 440 Hz, equivalent to a metronome "tic", ensuring a clearly audible volume. Moreover, to ensure participants were synchronised with the acoustic stimuli, recordings started 10 s after the stimulus was administered (Minino et al., 2021). For all participants, two gait acquisitions were recorded for each experimental condition. The trial started with the heel strike of one foot (e.g., the right foot) and ended with the second heel strike of the contralateral foot (e.g., the left foot). Hence, each recording contains at least one gait cycle per leg, since it specifically includes 1.5 strides for each side.

The Qualisys Track Manager software (QTM) was utilised to extract the three-dimensional position of 20 bone markers throughout the entire gait cycle, representing bone landmarks of interest for the intended whole-body analysis. Markers with low visibility and markers presenting redundant information were excluded, and one marker for each bone landmark was used for the network analysis, maintaining the left–right symmetry (Fig. 1). To minimise the effects of individual recording durations, all trials were interpolated to have the same number of data points, using the trial with the minimum duration as a reference. Following, for each marker we calculated the one-dimensional jerk time

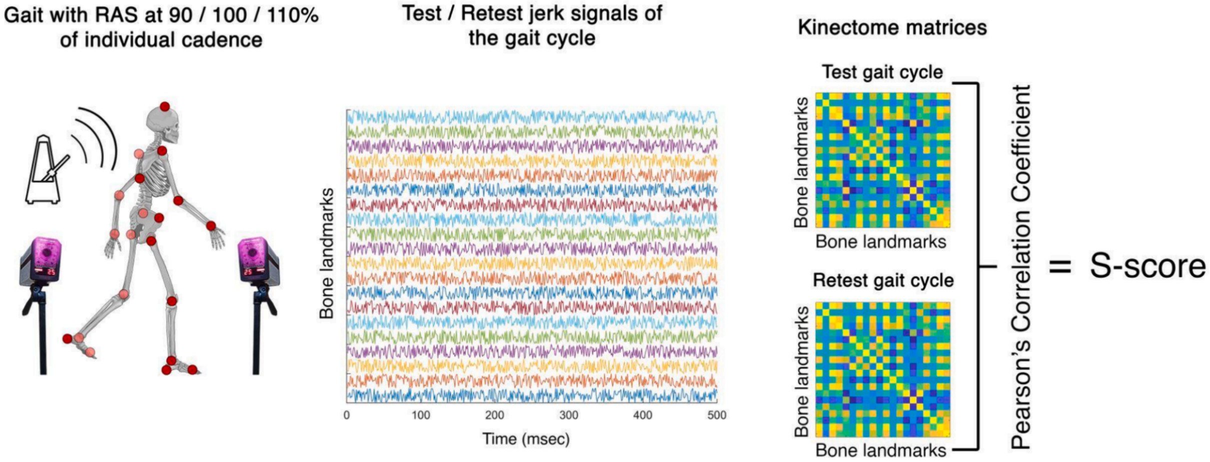

Fig. 1. Pipeline overview. On the left: Stereophotogrammetric acquisition. 13 healthy older adults were recorded through a stereophotogrammetric system, while walking during Rhythmic Acoustic Stimulation (RAS). Red dots represent the anatomical position of the bone marker. In the middle: Temporal series. The time series of the jerk are obtained from markers' positions placed on participants' body landmarks during the gait cycle. On the right: Kinectome matrices. Each matrix was built correlating one-dimensional jerk time series over two consecutive (left and right) gait cycles. In each experimental condition, two kinectomes for each participant were compared to calculate, through the Pearson's correlation, the Similarity Score (S-score). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

series (the first derivative of acceleration with respect to time), based upon the 3D coordinates of each given marker. Jerk was chosen as it displayed the highest individuals' differentiation as shown in Troisi Lopez et al. (Troisi Lopez et al., 2022).

2.3. Kinectome analysis

In this study, we applied the recently developed concept of kinectome to provide a description of gait characteristics in healthy older adults, taking into account the interaction between all body segments. The kinectome is a correlation matrix obtained by calculating the Pearson correlation coefficients between the time series of 20 bone landmarks of interest. Therefore, we identified the bone markers as nodes of the network, while the links (i.e., edges) were defined by the level of synchronisation between each pair of nodes (i.e., the correlation coefficients). We thus obtained a symmetrical matrix containing 380 edges, excluding the 20 diagonal elements, since they represent the correlation of a node with itself (Fig. 2). Furthermore, it should be considered that the actual information is stored in the half of the total number of edges (i.e., 190), as each matrix is symmetric with respect to the main diagonal.

2.4. Variability assessment

To measure the stability of participants' motor patterns, we compared the matrices (i.e., kinectomes) of each walking condition between the two trials (test and retest). The comparison was conducted by calculating the correlation coefficient between the two matrices, partially borrowing the methodological approach from network neuroscience studies that assessed the test–retest repeatability of brain connectivity matrices (Cipriano et al., 2023; Romano et al., 2022; Troisi Lopez et al., 2023) The obtained score was defined as Similarity Score

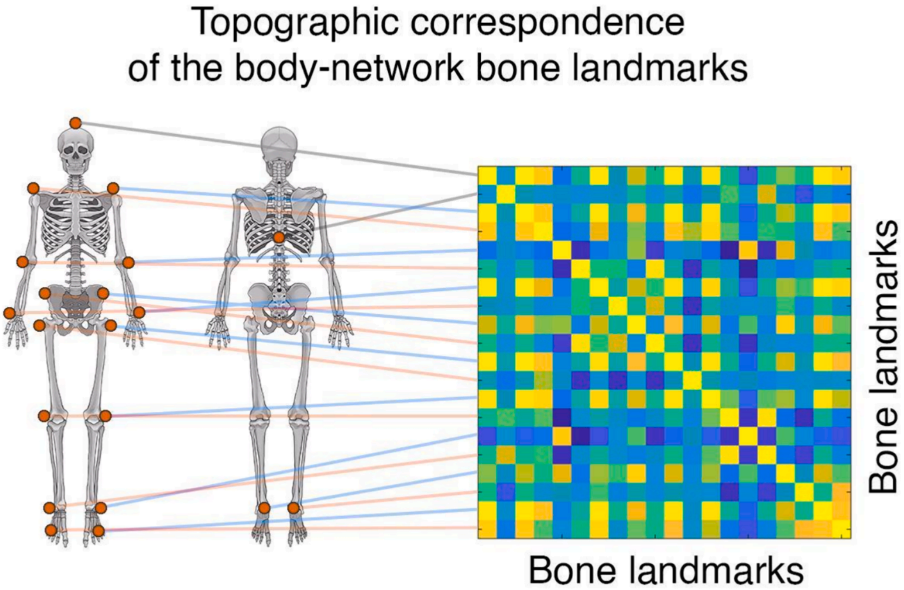

Fig. 2. Visual representation of the kinectome matrix. On the left, the 20 bone landmarks considered; on the right, the corresponding kinectome matrix. The lines connect each node to its position in the matrix. The elements within the matrix represent the correlation between each couple of bone landmarks' jerk time series.

(S-score), as it gives information with respect to how much a subject performs the movement in the same way. S-score, ranges from −1 to 1; scores close to 1 indicate a similar pattern between two trials, scores close to 0 represent highly different patterns. Scores close to −1 are unexpected as they would correspond to patterns of movement that are symmetrically opposite. It should be emphasised, however, that there may be cases where the various parts of the body vary the amplitude of movement but maintain the same correlation relationships. In this case, although the movement is different, the coordination between the parts can be considered unchanged. Additionally, we quantified gait and its variability using conventional parameters, the Spatiotemporal Parameters and their coefficients of variation (CV). Regarding spatiotemporal parameters, we calculated: Speed, Stride Width, Stride Length, Stance Time, Swing Time, Cycle Time AND Double Limb Support time (DLS time). The spatiotemporal parameters CVs, comprise the ratio between the standard deviation and the average value, expressed as a percentage (%), for all spatiotemporal parameters calculated, excluding the Speed (Liparoti et al., 2019). Both spatiotemporal parameters and CVs were corrected for BMI. Then, a statistical comparison between conditions was performed.

2.5. Statistical analysis

Statistical analysis was performed in Matlab (Mathworks version 2021a). Given the small sample size, it was not possible to reliably assess data distribution, hence we opted for non-parametric statistical tests. A Friedman's test and then a two-sided Wilcoxon signed-rank test was performed in order to observe a statistically significant difference between the baseline condition (SW) and the different experimental conditions (i.e., 100 %, 90 % and 110 %). The results were corrected for multiple comparisons using the False Discovery Rate (FDR) method (Benjamini & Hochberg, 1995). The significance level was set at $p < 0.05$.

3. Results

The Similarity Scores (S-scores) of the baseline condition and the three frequency conditions were compared through the Friedman test (Fig. 3), showing a significant difference ($\chi 2(3) = 10.94$, $p = 0.012$). In particular, the S-score of the experimental conditions of the RAS with 100 % and 90 % of the average cadence were statistically greater than the S-score of the SW ($p = 0.026$ and $p = 0.005$, respectively). No statistically significant difference was found in the comparison between SW and the RAS at 110 % of the average cadence ($p = 0.497$). When comparing the spatio-temporal parameters, the results show significant differences between the Baseline condition and the experimental conditions, for all analysed parameters, except for the Stride Width (as shown in Table 1). Regarding the coefficients of variation across each condition, we observed no significant differences in the variability of the CVs spatio-temporal parameters analysed.

4. Discussion

The aim of this work was to investigate the effect of RAS on gait variability, taking into account the kinematic relationship of all body segments. To achieve this goal, we used the "Similarity Score" (S-score) that measures how much the gait of an individual is similar to itself through multiple repetitions (i.e., two in this case). Our sample was subjected to three different acoustic stimulations frequencies, set at 100 %, 90 % and 110 % of their individual average cadence. The results of our analysis showed that acoustic stimulation leads to a reduction in movement variability. In particular, RAS at a frequency of 100 % and 90 % of each subject's mean cadence resulted in a reduction of motion variability, while any statistically significant variation with the 110 % frequency stimulation was observed.

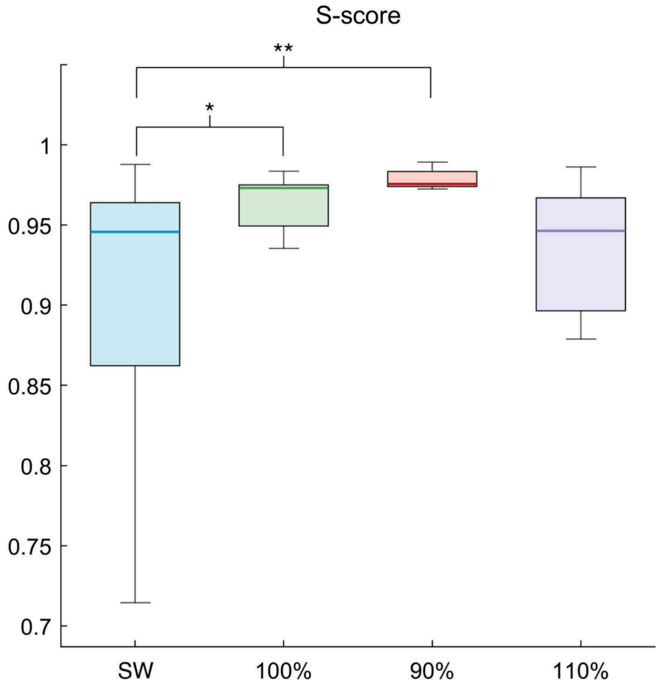

Fig. 3. Box plot of the Similarity Score (S-Score) when comparing the baseline walking condition (SW – Simple Walking) and the acoustic stimulation frequencies set at 100 %, 90 % and 110 % of the average cadence of each participant. The box plot includes data from 25 to 75th percentiles; the median is represented by the horizontal line inside each box; error lines reach the 10th and 90th percentiles; the outliers, if present, are represented by filled circles falling beyond 10th and 90th percentiles. Significance p value: * $p < 0.05$, ** $p < 0.01$.

Our results partly differ from the existing literature, which often does not highlight changes in gait variability with RAS in healthy older adults (Minino et al., 2021; Wittwer et al., 2013). Some studies even showed an increase in variability during walking with RAS. Recent research examined how musical properties influence synchronised and free walking in healthy young and older adults, considering rhythm perception. They showed that high groove music and metronome cues improve gait parameters, but low groove signals increased variability in step length, step time, and stride velocity"(Ready et al., 2022). Moreover, Hamacher et al. (2016), highlighted that a group of elderly people showed an increase in variability of stride time, but not in the variation of the Minimum Foot Clearance, compared to young people and people with diseases, such as Parkinson's disease(Hamacher et al., 2016). Indeed, Arias et al., demonstrated that RAS affects walking variability, decreasing coefficients of variability of stride time, which is known to be a parameter correlated with the reduction of fall risk(Arias & Cudeiro, 2010).

Anyway, when it comes to walking, it should also be considered that variability can be interpreted as a mechanism useful for learning and control (Wu et al., 2014). Several studies have indeed shown that a certain degree of variability is physiologically present in human walking rhythm, and it works as an adaptive strategy. Hunt et al., by recording the temporal series of participants' heel strikes, showed how it was possible to alter the fractal structure of the temporal pattern of cadence, bringing it closer to that of the colour of the noise used to produce the different stimuli (Hunt et al., 2014). This aspect is highly significant as it also highlights the plasticity of the synchronisation ability in human walking. However, the extent to which walking variability should be present is an extremely challenging question. This concept needs to be related to numerous other environmental variables such as walking speed, terrain, presence of hazards, etc. Furthermore, the response may also vary depending on the object of variability. For instance, in this study, we analysed the repeatability of the coordination patterns of

Table 1

Statistical comparison of Spatiotemporal Parameters and their Coefficient of Variations (CV) between conditions. Means and standard deviations, degrees of freedom (d.f), chi-square (χ2) and p values of Speed, Stride Width, Stride Width CV, Stride Length, Stride Length CV, Stance Time, Stance Time CV, Swing Time, Swing Time CV, Cycle Time, Cycle Time CV, Double Limb Support time (DLS time) and DLS Time CV.

	SW	100 %	90 %	110 %	d.f.	χ2	p value
Speed	0,042 (0,006)	0,044 (0,008)	0,039 (0,006)	0,049 (0,008)	3	28.58	< 0.001
Stride Width	0,004 (0,001)	0,004 (0,001)	0,004 (0,001)	0,004 (0,001)	3	2,395	0,49
Stride Lenght	0,047 (0,007)	0,049 (0,008)	0,047 (0,007)	0,049 (0,008)	3	15	0.002
Stance Time	0,027 (0,003)	0,028 (0,004)	0,032 (0,004)	0,026 (0,004)	3	31.15	< 0.001
Swing Time	0,016 (0,002)	0,016 (0,002)	0,017 (0,002)	0,014 (0,002)	3	25.15	< 0.001
Cycle Time	0,044 (0,005)	0,045 (0,007)	0,049 (0,006)	0,041 (0,006)	3	33.46	< 0.001
DLS Time	0,01 (0,002)	0,012 (0,002)	0,015 (0,002)	0,011 (0,002)	3	27.92	< 0.001
Stride width (CV)	18.89 (13.1)	14.12 (7.17)	15.41 (6.85)	15.79 (5.8)	3	2.08	0.557
Stride length (CV)	2.17 (0.94)	2.17 (1.21)	2.55 (0.69)	2.97 (1.95)	3	3.18	0.364
Stance Time (CV)	1.89 (0.48)	1.68 (0.83)	2.03 (1.21)	2.62 (2.99)	3	0.97	0.808
Swing Time (CV)	2.13 (0.63)	2.15 (0.8)	2.32 (0.79)	2.66 (1.24)	3	3.18	0.364
DLS Time (CV)	8.51 (2.1)	7.26 (2.2)	6.63(1.98)	6.91 (2.45)	3	7.63	0.055

walking expressed by body segments from various parts of the body. However, there are no in-depth studies on the variability of whole-body kinematic interactions during gait. To this regard, future studies can delve into this aspect, also observing the effect of variable stimuli on the walking pattern expressed by the entire body, by combining our approach for the estimation of coordination and variability with the administration of complex auditory (or visual) cues (Sotirakis et al., 2016; Vaz et al., 2020b).

It should be specified that the main difference between this study and the analyses already published in the literature lies in the methodological approach used. Starting from the hypothesis that human movement translates into a harmonious synergy of all parts of the body, we measured variability at a global level, considering the kinematic relationships between all parts of the body(Troisi Lopez et al., 2022). Previous studies, on the other hand, were limited to investigating possible differences in variability only with respect to specific parameters referring to individual body parts or derived measures (e.g., step length, step time, etc.). Our results suggest the idea that at the local level (i.e., individual body segments), variability may not be observed, and attention should be shifted to higher-order features(Troisi Lopez et al., 2022). Coordination indeed expresses the effectiveness with which we regulate spatial and temporal relationships between multiple elements (Bernstein, 1966). It is based on a very high number of degrees of freedom, and estimating its value through network theory allows us to capture movement characteristics of higher order and complexity, thereby assessing movement variability from a global perspective(Turvey, 1990). It should also be emphasised that we observed a reduction in variability only at frequencies equal to or lower than those of the participants, while during stimulation at a higher rhythm, no significant change was appreciated. We believe that in following rhythms within the threshold of the subject-specific cadence, the individual synchronises to the rhythm, managing to repeat movements in the same way. Once beyond their usual cadence rhythm threshold, maintaining control over all parts of the body can become a more challenging task, and therefore, participants were unable to stabilise coordination, despite the assistance of acoustic stimulation. Finally, our result is strengthened by the fact that, using classical methods for variability assessment (i.e., the coefficient of variation) within the same sample, we did not find any significant differences. Overall, our results reinforce the idea that a holistic approach to movement analysis may capture elements that are not measurable when examining individual segments, offering new perspectives for analysing the effects of sensory cues on gait patterns. It is necessary to consider the limitations of this study. A more comprehensive evaluation would require exploring the effect of different types of RAS (e.g., complex, non-linear stimuli) and evaluate the effects on different its performance in comparison to traditional approaches. It is important to emphasise that our study, analyses walking in a controlled environment, which is not typical of daily life movement. Next steps should focus on investigating these variations with respect to the risk of fall, to determine whether the increased repeatability of coordination patterns during gait due to RAS can be considered a beneficial outcome.

Furthermore, the small sample size could limit the generalisability of the results to a larger population. Unfortunately, although we aimed to continue the recruitment, the pandemic made it impossible, and to date we have not been able to resume the data collection. Expanding the sample to include a more diverse range of participants is necessary to confirm our preliminary results. Finally, further tests should be repeated including more trials to better assess variability.

5. Conclusions

In conclusion, this preliminary work highlighted the potential of rhythmic acoustic stimulation in increasing test–retest reliability in healthy older adults. While traditional analyses may not reveal a significant impact of RAS on movement variability, a comprehensive approach seems to highlight the systemic influence of RAS on movement repeatability across the entire body. The exploration of larger sample sizes and a comparison of diverse methodologies in future studies have the potential to offer additional confirmation and deeper insights into the utility and applicability of the kinectome and the S-Score parameter. This new evaluation could significantly contribute to our understanding of movement variability in various populations and conditions.

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CRediT authorship contribution statement

R. Minino: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **M. Liparoti:** Writing – review & editing, Resources, Investigation, Data curation. **A. Romano:** Writing – review & editing, Visualization, Methodology, Data curation. **F. Mazzeo:** Writing – review & editing, Data curation. **P. Sorrentino:** Writing – review & editing, Resources, Data curation. **D. Tafuri:** Writing – review & editing, Project administration, Investigation, Conceptualization. **E. Troisi Lopez:** Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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