Exploring the Role of Asymmetric Auditory and Tactile Stimulation on Modulating Gait Kinetics

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***Abstract*—This study explores the influence of Auditory Rhythmic Asymmetric Cueing (A-RAC), Tactile Rhythmic Asymmetric Cueing (T-RAC), and their combination (AT) on key kinetic gait parameters in gait rehabilitation: Vertical Ground Reaction Force Asymmetry (GRF), Push-off Force Asymmetry (POF), and Braking Force Asymmetry (BRK). Utilizing the Computer-Assisted Rehabilitation Environment (CAREN) with 18 participants, this research examines these interventions' effectiveness in generating asymmetric gait. While the results during adaptation indicate that BRK was significantly affected by both A-RAC ($p = 0.001$) and AT ($p = 0.003$), only A-RAC had a significant effect on GRF ($p = 0.002$) during adaptation. None of the interventions significantly altered POF, suggesting its resistance to sensory cue modification. These findings provide valuable insights for enhancing gait rehabilitation strategies, particularly in addressing vertical load distribution, controlled deceleration, and overall walking safety.**

***Keywords*—stroke rehabilitation, combination therapy, multimodal cues, neuro-motor deficits**

I. INTRODUCTION

Human locomotion, particularly gait, is a sophisticated motor skill vital to daily life, requiring a harmonized sequence of movements for effective balance and stability. This complex task becomes challenging for individuals with neuro-motor deficits, notably those affected by stroke. Stroke is a leading cause of long-term disability globally, disrupting mobility and normal gait patterns in more than half of stroke survivors aged 65 and older. In the United States alone, stroke-related expenses reached nearly $56.5 billion between 2018 and 2019 [1]. This underscores the urgent need for focused research and clinical interventions in gait rehabilitation. This research investigates a method of gait rehabilitation for stroke patients by examining the impact of Auditory Rhythmic Asymmetric Cueing, Tactile Rhythmic Asymmetric Cueing, and their combination on gait parameters such as Vertical Ground Reaction Force Asymmetry, Push-off Force Asymmetry, and Braking Force Asymmetry. These insights can lead to the development of personalized rehabilitation interventions that can improve mobility, quality of life, and functional independence for individuals with neurological motor deficits, especially those recovering from stroke [2,3].

Recent studies show asymmetric rhythmic stimuli cues could be a promising approach to gait rehabilitation, allowing more benefits compared to the traditional symmetric cues [4,5]. Symmetric cues, with equal beats for each leg, have demonstrated some efficacy in improving gait symmetry in stroke patients. Asymmetric cues, introducing controlled variability in walking rhythm, aim to stimulate neural plasticity and promote adaptable gait patterns, a departure from the norm of symmetry-based interventions. This area is crucial in unraveling the potential benefits and underlying mechanisms of asymmetric cueing in gait rehabilitation [6,7].

This research aims to understand the impact of rhythmic asymmetric cues on the gait pattern parameters of unimpaired individuals. The study focuses on three cueing modalities: Auditory Rhythmic Asymmetric Cueing (A-RAC), Tactile Rhythmic Asymmetric Cueing (T-RAC), and their combined form (AT). The specific parameters of interest include Vertical Ground Reaction Force Asymmetry, Push-off Force Asymmetry, and Braking Force Asymmetry. This study's primary goal is to assess the efficacy of these cueing modalities in influencing gait pattern asymmetries, similar to the gait patterns experienced by those suffering from neurological disorders. [8,9].

II. BACKGROUND

Gait symmetry, a complex neuromuscular coordination, can be disrupted by factors like injury or aging, affecting the neural network involving the cerebral cortex, cerebellum, and basal ganglia [10,11]. Stroke, in particular, leads to sensory impairments and changes in motor neuron activation, causing hemiparesis and significant gait asymmetries, which increase the energy cost of walking and the risk of falls [12,13,14]. Stroke-induced gait asymmetries include Push-off Force Asymmetry (POF), Vertical Ground Reaction Force Asymmetry (GRF), and Braking Force Asymmetry (BRK), arising from weakened muscle engagement in the paretic limb and reduced weight acceptance [2,3,15,16].

Rhythmic cueing has gained prominence in treating individuals with neuromotor deficits, leading to irregular gait patterns. Serving as external pacemakers, these cues help individuals with neurological deficits achieve more regular and symmetrical gait patterns [15]. The current study extends the

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application of rhythmic cueing to include asymmetric cues, aiming to understand its preventative potential and relevance in stroke patient rehabilitation.

Auditory cues, including rhythmic beats and musical rhythms, have gained attention in gait rehabilitation due to their ability to provide external temporal reference points, aiding in maintaining a more symmetric and coordinated gait pattern [17,18]. Research shows that these cues can significantly improve gait in stroke patients and other populations with gait impairments [9,10]. Both auditory and tactile rhythmic cueing have emerged as effective tools for addressing gait asymmetries [19,20,21]. Auditory cues, in particular, synchronize stepping patterns, enhancing gait symmetry and reducing falls across various neurological conditions [22,23,24].

Tactile cues involving vibrations or haptic feedback offer unique sensory input that enhances proprioception, spatial awareness, and improved timing during movement [8,9,44]. These cues are particularly relevant in addressing persistent limb asymmetry, often linked to neuromuscular changes such as altered muscle strength and proprioception in neurological conditions like stroke [9,10]. Tactile feedback provides real-time information about gait and balance, potentially assisting individuals in correcting gait asymmetries [25,26]. The exploration of tactile cues in gait rehabilitation represents a novel and promising area of research, showing promise in enhancing balance, muscle activation, and gait symmetry [27,28].

Motor adaptation and learning are key in gait rehabilitation. Motor learning leads to sustained changes, while motor adaptation involves only modifying mastered movements in new contexts, however, consistent training that induces motor adaptation can lead to motor learning [29,30,42]. Audio and tactile stimulations harness use-dependent and instructional motor learning mechanisms, with tactile stimulation potentially also engaging sensorimotor adaptation [31,32].

The combination of auditory and tactile cues (AT) aims to harness the complementary benefits of both sensory inputs, adopting a multi-sensory approach that may provide a more comprehensive and effective strategy for enhancing gait symmetry and control [13,14]. The integration of auditory and tactile systems in rehabilitation seeks to determine whether this combined cueing method yields superior outcomes compared to using each modality independently. Additionally, combining treatments like audio-tactile simultaneous combination cueing (AT) has demonstrated the potential to enhance gait parameter symmetry more effectively than single modalities. This multimodal approach leverages the interdependent effects of both sensory modalities [33,34,35].

A-RAC and T-RAC processing in the brain involves multiple neural pathways. A-RAC is processed through the auditory cortex, aiding in gait coordination, while T-RAC, detected by Pacinian corpuscles, is processed through the somatosensory cortex, essential for interpreting tactile feedback. The integration of these stimuli in the association cortices aids in planning and executing voluntary movements [36,37]. The motor cortices, basal ganglia, and cerebellum refine motor commands for precise gait pattern adjustments, demonstrating the efficacy of these cueing methods in gait rehabilitation [38,39].

The exploration of A-RAC, T-RAC, and AT in this study is expected to yield valuable insights into their respective and combined effects on critical gait parameters. By focusing on GRF, POF, and BRK, the research aims to elucidate the specific ways in which auditory and tactile cues, both separately and together, can influence gait dynamics. This could lead to a more nuanced understanding of gait rehabilitation techniques, opening the door for more targeted and effective treatments for stroke patients and potentially others with similar neuro-motor deficits [16,40].

III. Methods

This research was designed as a controlled experimental study to evaluate the impact of A-RAC, T-RAC, and AT on key kinetic gait parameters: GRF, POF, and BRK. The study involved 18 able-bodied participants to simulate the post-stroke gait conditions. Participants were selected based on specific criteria, including being college-aged individuals (19-26 years of age), physical health (being able to walk at least 0.85 [m/s]), an average step time asymmetry and step length asymmetry within ± 6% and absence of any neurological disorders, injuries to the lower limbs in the last 12 months, or special single-leg training that could influence gait. The study aimed to provide a generalized understanding of the effects of these cueing methods on gait parameters, thereby informing rehabilitation strategies for stroke survivors.

The Computer-Assisted Rehabilitation Environment (CAREN) system was used in this study. The CAREN is a virtual reality system that includes a split-belt treadmill equipped with force plates, a 180-degree projection screen, and a multi-camera motion capture system. Kinetic measurements were taken using a combination of data from the force plates, and 11 reflective markers at the following locations: the xiphoid process of the sternum, the left and right trochanter major of the femur, the left and right lateral epicondyle of the knee, the left and right lateral malleolus of the ankle, the left and right heel, and the left and right second toe.

Participants were recruited from the University of South Florida. Ethical approval was granted by the Institutional Review Board, with a comprehensive informed written consent process undertaken for each participant. Participants underwent a limb-dominance assessment and met the specific inclusion and exclusion criteria mentioned above [41].

A. *Description of Stimuli Setup and Application Protocol*

- A-RAC: The auditory cues were recorded, spoken cues played via speakers on the CAREN system and calibrated to match half of the average stride time for each participant. The timing of the cues was designed to be initially symmetric (1:1 ratio) at the end of the 3-minute baseline and began becoming increasingly asymmetric during the 2-minute transition phase before reaching and maintaining the 2:1 ratio during the 13-minute adaptation phase (as shown in Figure 1). Participants were instructed to follow the cues in order to induce changes in the targeted kinetic gait parameters.

- T-RAC: Tactile cues were provided under the subject's feet using AEDIKO® brand encapsulated vibration motors. These motors were part of a custom-designed haptic device, controlled by an Arduino Uno R3. The device received signals from CAREN's D-Flow software and operated the motors at a verified frequency of 257.7 ± 6.7 Hz. The setup aimed to maximize participant comfort and safety, with vibration motors strategically placed under the second and third toes to maximize localization accuracy, since the tactile cue is an indicator for initiating a step and to target areas dense in Pacinian corpuscles, known for their sensitivity to high-frequency vibrations [36,37,43]. The wiring was arranged along the participants' legs and connected to the haptic device, which was securely attached to the participants' clothing. This setup minimized interference with movement and reduced potential hazards. The vibration patterns were asymmetrically aligned with the participant's gait cycles, aiming to induce alterations in the kinetic parameters.
- AT: The AT protocol combined both auditory and tactile stimuli, delivering them simultaneously to study the synergistic effects on the kinetic gait parameters.

The experimental design consisted of four sessions per participant, with a vibration motor setup to apply timed stimulation to the bottom of the feet, and reflective markers on key anatomical landmarks to track the lower limb movements. The trial sequence was determined by a Latin square randomization to ensure an even distribution of the different cue modalities among participants. Each experimental session lasted 23 minutes, comprising a baseline phase, a transition phase (where cues shifted from symmetric to asymmetric), an adaptation stage, and a post-adaptation stage, designed to assess the retention of induced asymmetries (as shown in Figure 1).

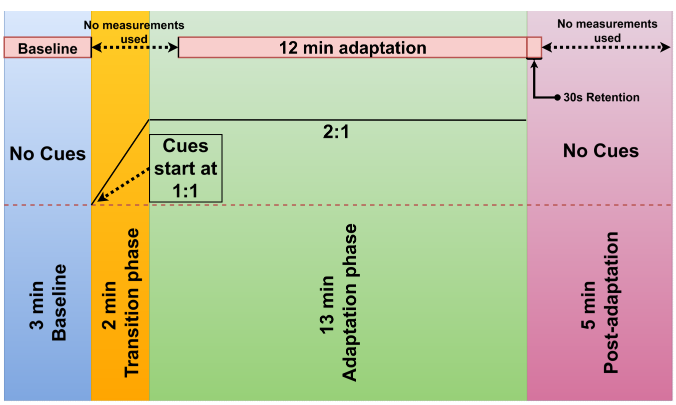

Figure 1: Timeline of the 23-minute experiment showing the different phases. Stimuli cues start at 1:1 at the end of the 3-minute baseline, increase to a 2:1 ratio during the 2-minute transition phase, and remain at 2:1 during the 13-minute adaptation phase.

B. *Data Collection and Analysis Methods*

Data were captured at a rate of 100 Hz and analyzed using MATLAB R2022b. A combination of marker trajectories and force plate readings were used to assess gait parameters. The data processing involved noise filtration and the identification of key gait events, such as heel strikes and toe-offs, through a combination of marker position and force data. A standardized equation calculated the percent asymmetry for POF, GRF, and BRK, with averages determined during each experimental phase.

Gait parameter asymmetries were measured using the following equation:

$$Asymmetry = \frac{(L-R)}{\frac{1}{2}(L+R)}\ [\%] \quad (1)$$

The statistical analysis uses IBM SPSS 29.0. The Shapiro-Wilk test evaluated the normality of the data distribution, followed by either ANOVA or Friedman's test, depending on the data's normality, to compare means across experimental stages. In cases where significant differences were observed, a Wilcoxon signed-rank test further pinpointed the stages or conditions showing notable variations. This statistical approach examined the effects of A-RAC, T-RAC, and AT cueing modalities on the targeted gait asymmetries.

IV. Results

This experiment consisted of 18 unimpaired, college-aged participants (9 male, 9 female) who had a comfortable average gait velocity of 1.17 ± 0.1 [m/s], average stride time of 1.13 ± 0.08 [s], average step length asymmetry of 2.38 ± 0.09%, and average step time asymmetry of -0.42 ± 1.82%. Of these subjects, 13 were right limb dominant, 3 were left limb dominant, and 2 were cross-dominant. Cross-dominant refers to when an individual switches between dominant limbs depending on the task. Because over half of the data were non-normal, a Wilcoxon sign-rank test was used to measure all statistical significance. Additionally, since the kinetic gait parameters are part of a larger data set, the p-value was set to 0.005 instead of 0.05 using a Bonferroni correction to eliminate the type I error.

A. *Vertical Ground Reaction Force (GRF) Asymmetry*

The results, as shown in Table I, revealed a significant impact of A-RAC on GRF during the adaptation phase. Blue means the results are statistically significant from the baseline. Red means the values are not statistically different from the baseline.

Table I - GRF in Response to Stimuli

GRF	12-minute Adaptation		30-second Retention Post Adaptation	
	Z	p	Z	p
A-RAC	-3.027	0.002	-1.938	0.053
T-RAC	-	-	-	-
AT	-2.461	0.014	-2.591	0.010

B. *Push-off Force (POF) Asymmetry*

As shown in Table II, none of the interventions significantly altered POF, which is critical for efficient propulsion during gait and reflects the capacity of each leg to contribute to forward momentum. Red means the values are not statistically different from the baseline.

Table II - POF in Response to Stimuli				
POF	12-minute Adaptation		30-second Retention Post Adaptation	
	Z	p	Z	p
A-RAC	-2.199	0.028	-0.762	0.446
T-RAC	-0.936	0.349	-2.461	0.014
AT	-2.025	0.043	-1.764	0.078

C. *Braking Force (BRK) Asymmetry*

Regarding BRK, which is crucial for controlled deceleration and stability during gait termination, both A-RAC and AT showed notable effects as shown in Table 3. Note that A-RAC vs. T-RAC during adaptation just missed the required statistical significance of $p < 0.005$; the differences in asymmetry should be further studied. Blue means the results are statistically significant from the baseline. Red means the values are not statistically different from the baseline. Yellow means the results just missed statistical significance.

Table III - BRK in Response to Stimuli				
BRK	12-minute Adaptation		30-second Retention Post Adaptation	
	Z	p	Z	p
A-RAC	-3.201	0.001	-0.936	0.349
T-RAC	-1.894	0.058	-1.111	0.267
AT	-2.940	0.003	-0.414	0.679
A-RAC vs T-RAC	-2.722	0.006	-0.457	0.647

V. Discussion

This study analyzed the effects of A-RAC, T-RAC, and AT on three critical kinetic gait parameters: GRF, POF, and BRK. These parameters are integral to understanding and improving gait in post-stroke rehabilitation.

The study's findings reveal that A-RAC significantly reduces GRF, indicating that auditory cues are effective in modulating vertical load distribution during gait. This reduction in GRF asymmetry, a key factor in differential loading patterns between the legs, is crucial for maintaining balance and stability during walking. The influence of A-RAC on this parameter has substantial clinical implications, particularly for stroke survivors who are at an increased risk of falls due to balance problems. By enhancing GRF symmetry, A-RAC may improve postural stability and reduce the risk of falls in this population. On the other hand, T-RAC showed a lower impact on GRF, suggesting that tactile cues are less effective in this regard. Additionally, the combination of auditory and tactile cues (AT) presented intermediate effects on GRF, indicating a synergistic but not additive effect in enhancing balance and weight distribution.

The interventions did not demonstrate a significant impact on POF, a key parameter for propulsion in gait, suggesting that this aspect of gait may be more resistant to modification through external sensory cues alone. This lack of significant changes underscores the complexity of influencing the push-off phase in gait rehabilitation. These findings highlight the necessity for more targeted or combined therapeutic approaches, as well as the potential need for additional or alternative strategies to effectively address propulsion in gait rehabilitation.

Both A-RAC and AT demonstrated notable effectiveness in modifying BRK. This aspect of gait is critical for the safe deceleration and stopping of movement. The ability to modulate BRK can greatly benefit post-stroke individuals who often struggle with controlling movement, thereby enhancing their walking safety.

A-RAC emerged as the most effective method in influencing GRF and BRK, underscoring the potential of auditory cues in post-stroke gait rehabilitation. T-RAC, while less effective, still presents a viable option for patients who might respond better to tactile stimuli. The combination method (AT), although not showing additive effects, offers a multimodal approach that can cater to different sensory preferences and may prove beneficial in a broader patient population.

The study's results indicate that auditory cueing, particularly A-RAC, can be a valuable tool in clinical practice for improving balance and safety in gait among stroke survivors. A-RAC's observed effects on both GRF and BRK are promising, highlighting its significant role in correcting imbalances in gait dynamics post-stroke. Rehabilitation programs might integrate A-RAC to specifically target and improve these parameters. However, considering the non-significant results for POF, clinicians should consider combining sensory cueing with other therapeutic exercises focusing on lower limb strength and coordination for a more comprehensive rehabilitation approach.

The limited effectiveness of T-RAC and the moderate impact of AT suggest that while tactile cues alone may not be sufficient in addressing kinetic gait parameters, their combination with auditory cues could offer a more comprehensive approach. The results underscore the importance of considering individual sensory modalities and their combinations in designing gait rehabilitation programs for stroke survivors. Particularly, A-RAC's ability to influence key aspects of gait, such as balance (via GRF) and safety (via BRK), can be integrated into rehabilitative practices. However, the resistance of POF to these interventions highlights the need for further research to develop more effective strategies for enhancing propulsion in gait rehabilitation.

A. *Limitations of the Study*

The primary limitation is the use of able-bodied individuals to simulate post-stroke conditions. It was preferable to initially test on healthy subjects to study the best possible outcome for T-RAC and to minimize the effects of confounding variables stemming from the significant variability of symptoms presented in neuro-deficit individuals; however, future research should involve actual stroke survivors to validate the results, as they use different neural and muscular pathways compared to healthy subjects. Stroke subjects may also have a reduced sensitivity to tactile stimulation compared to healthy subjects. The study's sample size and lack of diversity also limit the generalizability of the findings. Moreover, the short-term nature of the interventions calls for further research on the long-term effects of these cueing methods.

VI. Conclusion and Future Work

Future research should focus on larger, more diverse populations, including stroke survivors, to enhance the generalizability of the findings. Longitudinal studies are needed to assess the long-term efficacy of these interventions. Investigating the integration of these cueing methods with other rehabilitation techniques, such as strength training and balance exercises, could provide a more holistic approach to gait rehabilitation. Additionally, exploring related technological advancements, such as virtual reality and wearable sensors, could offer additional ways to implement these cueing methods in clinical settings.

In summary, the study contributes significantly to the understanding of sensory cueing in gait rehabilitation post-stroke. The minimal effect on POF highlights the necessity for more comprehensive rehabilitation approaches that encompass all facets of gait. Future research should explore the use of sensory cues to initiate toe-off instead of modifying the timing of heel strike, as employed in this study, potentially yielding improved outcomes for POF. The findings, particularly regarding the efficacy of A-RAC in modulating GRF and BRK, offer promising avenues for clinical application in enhancing gait stability and safety in stroke survivors.

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