Gait Response to Rhythmic Cues: Influence of Adaptation Mechanisms and Entrainment Levels

Adila Hoque
Department of Mechanical Engineering
University of South Florida
Tampa FL, USA
adila1@usf.edu

Dr. Seok Hun Kim
School of Physical Therapy and Rehabilitation Sciences
University of South Florida
Tampa FL, USA
seokhunkim@usf.edu

Dr. Kyle B. Reed
Department of Mechanical Engineering
University of South Florida
Tampa FL, USA
kylereed@usf.edu

***Abstract* — This study categorizes the response to asymmetric rhythmic cues into distinct levels of adaptation using changes in their step velocity. Motion capture and force data were collected from healthy individuals undergoing split-belt treadmill and rhythmic cueing interventions. This allowed comparative insights into two distinct adaptation mechanisms (sensorimotor and instructional adaptation) corresponding to the interventions and integration of those findings with trade-off mechanisms within spatiotemporal and kinetic gait parameters. Interlimb gait harmony (corresponding to differences between left and right step velocities) was significantly different between the gait interventions, indicating underlying differences in the dominant adaptation mechanisms driving them. The trade-off mechanisms among step length, swing time, and push-off forces were significantly different (i) between the gait interventions and (ii) between adaptable and non-adaptable subject groups to external rhythmic cues. This suggests that an orthogonal linear relationship between propulsion and either spatial or temporal features may indicate the adaptation mechanism that has a greater contribution towards their motor outcome.**

Keywords—rhythmic cueing, push-off force, sensorimotor adaptation, sensorimotor synchronization, proprioception, split-belt treadmill, gait harmony

I. Introduction

Rhythmic auditory cueing (RAC) is a gait rehabilitation technique using auditory cues to indicate step timings. For an individual with an asymmetric gait pattern, the rhythmic auditory cues function as a template for the individuals to match the timing of their footfalls. This template constitutes symmetric bilateral auditory cues in the form of a metronome, a musical beat, or verbal signals [1].

Although RAC directly targets the timing of gait initiation and termination, it has proven effective with other gait parameters as well. These parameters include step length, cadence, stride length, push-off force, and gait velocity [2, 3, 4, 5]. However, previous studies have found that there was considerable variability in the effectiveness of RAC, most of which was linked to individual rhythm abilities within the subject population [6, 7]. The effectiveness of RAC in entrainment and synchronization have been evaluated using measures such as tempo-matched cadence, relative phase angle, (a)synchrony, and TGA (temporal gait asymmetry) [7, 8]. Crosby et al. [7] determined TGA using the asymmetry in single-limb support time between the left and right legs. A variation of this measure is also described as a metric for gait harmony by Iosa et al. [9, 10]. Gait harmony is an intralimb parameter quantified by the swing-to-stance time ratio (SSR) [9]. It is reflective of the rhythmic pattern of gait and correlates linearly with step velocity [11, 12]. Speed-based asymmetric walking, e.g., split-belt treadmill (SBT), is likely to disturb the interlimb gait harmony.

In this study, linear dependency of SSR on step velocity was applied to asymmetric walking via different adaptation mechanisms to define a metric for the ability to adapt to rhythmic cues. Two interventions were chosen for their distinct adaptation mechanisms: split-belt treadmill (SBT) and asymmetric rhythmic auditory cues (ARAC). ARAC is like RAC but involves adjusting the left and right cue durations such that the step time of one leg is less than the other, while maintaining the individual's comfortable stride time [13]. SBT and ARAC are asymmetric interventions that place the same temporal demands on the lower body, while engaging different adaptation mechanisms. A study by Rasouli et al. found that the effects of SBT and ARAC on one's gait combine additively during adaptation, indicating that they engage independent and concurrent dominant adaptation mechanisms [13].

Adaptation to SBT is autonomous and driven via proprioceptive errors as the treadmill belts change their speeds – a mechanism known as "sensorimotor feedback." Alternatively, "instructional" adaptation to ARAC requires the participant's active compliance to entrain their gait with the external rhythmic cues [14]. Entrainment refers to the alignment of rhythmic activity between multiple systems, whereas "adaptability" refers to the subjects' ability to adjust their rhythmic activity (i.e., gait pattern) to changes in their environment – which may or may not be rhythmic [1, 14]. A study using SBT found that exaggerating propulsion demands increased step length asymmetry, revealing a trade-off with push-off forces – a correlation that persisted with clinical subjects [15, 16]. This study attempts to elucidate interaction patterns between multiple gait features within the context of the two adaptation mechanisms and levels of entrainment.

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II. Materials and Methods

A. Objectives and Rationale

Gait asymmetry during SBT training was modeled as an "ideal" attainable interlimb gait asymmetry. This limit was used to set the optimum standard for successful gait entrainment of healthy individuals to asymmetric rhythmic auditory cues. This was followed by a comprehensive approach to model potential trade-offs between gait parameters in the spatial, temporal, and kinetic domains. The outcomes of this study would (i) enable quantitative comparisons in the efficacy of sensorimotor and instructional adaptation during training, and (ii) optimize rhythmic cueing strategies to target gait impairments by balancing (or exaggerating) any "trade-off" mechanisms in other domains. The two main study objectives are stated as follows.

- *Ability to adapt to rhythmic cueing*

The difference between the tread speeds in SBT or between the left and right step times in ARAC may lead to disparate step velocities, disrupting interlimb gait harmony. This disruption is reflected in the asymmetry between the left and right leg's swing-to-stance time ratio, SSRA (%). Since gait harmony is correlated with step velocity, it was hypothesized that successful rhythmic synchronization would result in an SSRA that is correlated with the asymmetry of the applied gait intervention. ARAC was applied as the subjects walked on a tied-belt treadmill (TBT), which may affect their ability to synchronize the timing of their steps with the external cues. The symmetric nature of TBT "forces" individuals to walk symmetrically, which interferes with the temporal demands placed by ARAC [27]. To address this, SBT training incorporated symmetric rhythmic auditory cues (RAC), strategically engaging both instructional and sensorimotor adaptation mechanisms for the two gait interventions.

- *Trade-offs in gait adaptation, adaptation mechanisms, and ability to adapt to rhythmic cueing*

Although rhythmic cueing targets step time, effects have been observed in other gait parameters as well, such as step length and gait kinetics [2]. This study models the response to rhythmic cues as a "trade-off" mechanism among spatial, temporal, and kinetic gait parameters, exploring different adaptation mechanisms (sensorimotor and instructional) and "adaptability" levels, indicated by a disturbance in their interlimb gait harmony.

B. Experiment Design

Experiments were performed using the Computer Assisted Rehabilitation ENvironment (CAREN, Motek Medical). The CAREN is equipped with a treadmill with a split-belt setting, Bertec force plates, 10 Vicon cameras, a 180-degree projection screen and surround sound to deliver the verbal "left" and "right" cues. Infrared reflective markers were placed on the participants' sternum, lateral trochanters, menisci, malleoli, toes, and heels for motion capture. Marker trajectory and force plate data were collected using the D-Flow program at 100Hz, followed by analysis using a custom-made gait analysis program in MATLAB.

Gait study		Simultaneous combination	Sequential combination
Number of sessions		4	6
Subjects		n = 16	n = 11
Single **asymmetric** interventions	**SBT** + RAC (1:1)	• SBT was applied at a ratio of **2:1** for group A (n = 8) and at **1:2** for group B (n = 8). (Trial 2, [13]) • Both groups also received symmetric rhythmic auditory cues during SBT adaptation. • Left belt speed was twice that of the right belt for group A, and half of the right belt for group B.	• SBT was applied at a ratio of **2:1** with symmetric rhythmic auditory cues (1:1) for all subjects (n = 11). (T-S, [17]) • Left belt speed was twice that of the right.
	ARAC + TBT (1:1)	• ARAC was applied at a ratio of **1:2** on a tied-belt treadmill (1:1) for both groups (n = 16). (Trial 1, [13]) • Left assigned step time was twice that of the right.	• ARAC was applied at a ratio of **2:1** on a tied-belt treadmill (1:1) (n = 11). (T-C, [17]) • Left assigned step time was half that of the right.

Fig. 1. Description of the SBT and ARAC experiments in the two gait studies. Both studies had the same protocol for the ARAC (Trial 1 in [13] and T-C in [17]) and SBT (Trial 2 in [13] and T-S in [17]) sessions but different conditions for the remaining trials. Only the matching sessions were used in this study.

Data were collected from two gait studies that investigated the effects of simultaneous and sequential combinations of SBT and ARAC on gait symmetry of healthy individuals with an unimpaired gait pattern [13, 17]. The two studies were randomized in trial order and had a repeated-measures design, and their protocol was approved by the University of South Florida Institutional Review Board. The asymmetric interventions, i.e., SBT and ARAC, were applied at a ratio of 2:1 (Fig. 1). Written informed consent was obtained from subjects. They were then asked to walk at their self-reported comfortable speed on a tied-belt treadmill to determine their comfortable stride time and spatiotemporal asymmetry. If they met the eligibility criteria, the self-reported comfortable gait speed and corresponding stride time were used to modulate their SBT and ARAC trials. During the SBT and ARAC experiments, participants were asked to follow the auditory cues as they walked on the treadmill.

For SBT, the fast belt was increased to 4/3 of their comfortable walking speed, and the slow belt was set to 2/3 of their comfortable walking speed. For ARAC, the same temporal asymmetry was applied by assigning a "slow" step time equal to 2/3 of their stride time at comfortable speed, and a "fast" assigned step time equal to 1/3 of their comfortable stride time. The average speed and average stride time were unchanged in both interventions. Both experiments involved 23 minutes of uninterrupted walking on a treadmill: 3 minutes of baseline (no perturbation), followed by 15 minutes of exposure to an asymmetric intervention, and 5 minutes of post-adaptation (no perturbation).

C. Data Analysis

Motion capture and force plate data were processed using MATLAB 2022a. Marker location and force plate data were reversed laterally for the following datasets from one of the gait studies [13] to ensure consistency in direction of asymmetry between the datasets (Fig. 1):

- Trial 2 (i.e., SBT (1:2) + RAC), Group B (n = 8) from Rasouli et al. [13].
- Trial 1 (i.e., ARAC (1:2) + TBT), all subjects (n = 16) from Rasouli et al. [13].

Kinetic parameters and heel marker trajectory were used to determine asymmetries of the following gait parameters: step length (SLA), step time (STA), swing time (SWG), stance time (STN), peak push-off force (POF), and peak braking force (BRK). Asymmetries were calculated using the symmetry index shown in Equation (1) [18].

$$\% \, Asymmetry = \frac{Left\ step\ -\ right\ step}{mean(left\ step,\ right\ step)} \times 100 \qquad (1)$$

Asymmetries were then passed through a 1st order Butterworth filter with a cutoff frequency of 50Hz. Gait harmony was calculated using the ratio of swing-to-stance time (SSR), and the disturbance in interlimb gait harmony was calculated using their asymmetry (SSRA).

The SSRA for an individual walking at an asymmetric step velocity of 2:1 corresponds to an SSRA of 66.67% according to Equation (1). The distribution of SSRA during SBT adaptation was used to calculate the threshold at which the concavity shifts. This threshold accounts for the potential limiting effects of the tied-belt treadmill on the subjects' ability to adapt to ARAC. Subjects were categorized as "partially adaptable" if their average SSRA during adaptation to ARAC was within 2 standard deviations of this threshold. Subjects that did not reach the lower limit of this range were categorized as "non-adaptable," and those that exceeded the upper limit were categorized as "adaptable."

A linear multivariate regression model was generated to reflect changes between spatial, temporal, and kinetic asymmetric gain. This model was then adapted to the three levels of rhythmic adaptability.

Upon confirming the normality of their distribution using the Shapiro-Wilk test, a two-way analysis of variance (ANOVA) was performed on the three chosen gait parameters and SSRA to determine the effects of the dominant adaptation mechanism (indicated by the intervention type) and the adaptability levels.

III. Results

A. Subjects

Baseline SLA and STA were reevaluated for the combined dataset. One participant from the sequential combination study was excluded because their baseline SLA exceeded 3 standard deviations of the average. Two additional subjects from the simultaneous combination study were excluded due to a large SLA that exceeded 3 standard deviations of the remaining subject population (n = 26) during adaptation to ARAC. The two subjects had an average SLA of 36.76% and -85.15%, and their outlier status were verified using Z-scores: (i) -4.39 and (ii) 4.08. Tukey's fences also verified that their SLA exceeded the upper and lower fences (-12.67,13.77%). The final dataset comprised

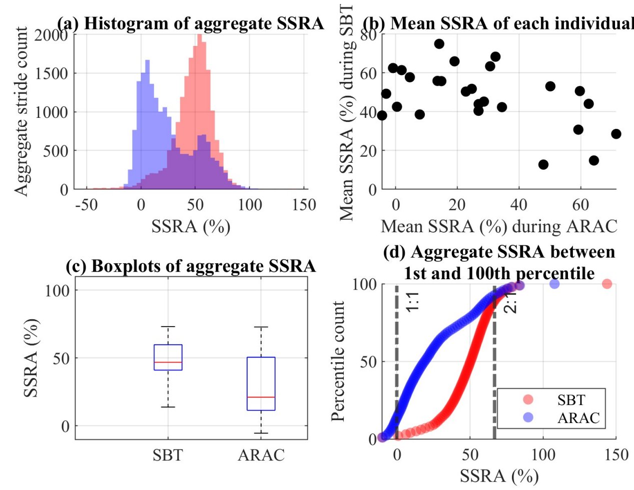

Fig. 2. SSRA distribution during SBT and ARAC adaptation.

24 subjects with an average comfortable walking speed of 0.98 ± 0.193m/s and average stride time of 1.21 ± 0.18s.

B. Adaptability to rhythmic auditory cueing

The percentile distribution of SSRA (mean = 47.76%) during SBT adaptation exhibited a sigmoidal trend (Fig. 2(d)). Its inflection point was found to be at the 20th percentile, corresponding to an SSRA of 35.97%. Subjects were categorized as "partially adaptable" if their average SSRA during ARAC (mean = 27.94%) was between 20.2% and 41.3%. Subjects were categorized as non-adaptable if their average SSRA did not reach the lower limit of 20.2%, and subjects were considered adaptable if their average SSRA exceeded the upper limit, 41.3%. This resulted in 10 "non-adaptable" subjects, 7 "partially adaptable" subjects, and 7 "adaptable" subjects (Fig. 4).

Normality of SSRA distributions were verified using the Shapiro-Wilk test for SBT (W = 0.964, p = 0.533) and ARAC (W = 0.933, p = 0.108). A two-way ANOVA revealed that the effects of (i) intervention type (F(1,42) = 25.51, p = 9.0e-06), (ii) adaptability level (F(2,42) = 10.46, p = 2.06e-04), as well as their interaction effects (F(2,42) = 52.31, p = 3.90e-12) on SSRA were statistically significant. In addition, a linear regression model was fit to the relationship between gait harmonies from SBT and ARAC as shown in Equation (2), $R^2 = 0.24$, p = 0.016.

$$SSRA_{ARAC}\ (\%) = 63.41 - 0.74 * SSRA_{SBT}\ (\%) \qquad (2)$$

Post-hoc pairwise comparisons showed that SSRA was significantly greater during SBT compared to ARAC for partially adaptable (p = 0.002) and non-adaptable subjects (p = 4.8e-12), but not for adaptable subjects (p > 0.05). SSRA of adaptable subjects was significantly higher compared to subjects in the other categories for SBT (non-adaptable: p = 0.003; partially adaptable: p = 0.022) and ARAC training (non-adaptable: p = 5.75e-12, partially adaptable: p = 3.57e-05). Partially adaptable subjects had a significantly greater SSRA than non-adaptable subjects during ARAC training (p = 8.19e-04), but not SBT (p > 0.05).

C. *Trade-off mechanisms*

Asymmetries in kinetic parameters, POF and BRK, were correlated with all temporal parameters {i.e., step time (STA), swing time (SWG), and stance time (STN)} for ARAC. Correlation between SLA was statistically significant ($p < 0.05$) with POF, but not with BRK ($p > 0.05$) during SBT (Fig. 3). For ARAC, correlation between POF and all temporal parameters were statistically significant ($p < 0.05$), with the highest magnitude of correlation against SWG (Fig. 3). A linear model was generated for trade-off mechanisms within the following parameters: POF, SLA, and SWG. Since SLA and SWG were not correlated during either intervention, they were the predictor variables in the regression model, as shown in Equation (3).

$$POF = S*(SLA) + T*(SWG) + k \quad (3)$$

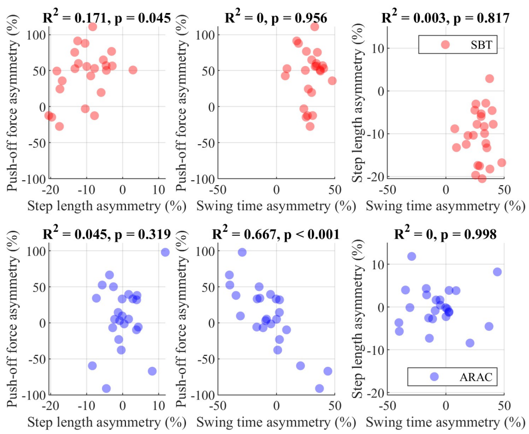

Fig. 3. Linear relationship between gait parameters.

Table I shows the model's spatial and temporal coefficients, "*S*" and "*T*," from Equation (3), and goodness-of-fit for all subjects and within the adaptability levels. The linear models were statistically significant ($p < 0.05$) for ARAC but not for SBT (Table I, Fig. 5). Fig. 4 and Table II exhibit the average gait asymmetries and corresponding statistical outcomes.

TABLE I. MODEL PARAMETERS AND FIT FOR SBT AND ARAC. COEFFICIENTS MARKED WITH AN ASTERISK INDICATE STATISTICALLY SIGNIFICANT CORRELATION ($p < 0.05$*) OF THE CORRESPONDING PARAMETER WITH POF.

	Model parameter and fit		**All subjects**	**Non-adaptable**	**Partially adaptable**	**Adaptable**
ARAC	Parameter	*S*	1.984	5.018*	2.121	-2.276
		T	-1.682*	-1.854*	-1.747	-2.173*
		k	-2.251	0.814	0.471	-19.833
	Model fit		$R^2 = 0.71$, $p < 0.0001$	$R^2 = 0.85$, $p = 0.001$	$R^2 = 0.68$, $p = 0.1$	$R^2 = 0.85$, $p = 0.024$
SBT	Parameter	*S*	2.491*	3.294	-2.867	4.589*
		T	-0.034	0.243	0.975	0.634
		k	70.351	79.161	9.356	27.392
	Model fit		$R^2 = 0.17$, $p = 0.140$	$R^2 = 0.23$, $p = 0.402$	$R^2 = 0.096$, $p = 0.81$	$R^2 = 0.67$, $p = 0.108$

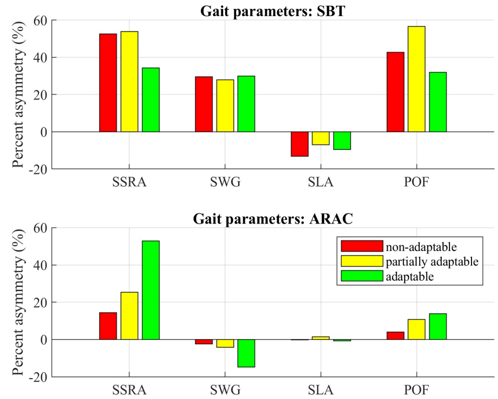

Fig. 4. Gait asymmetries within the adaptability levels.

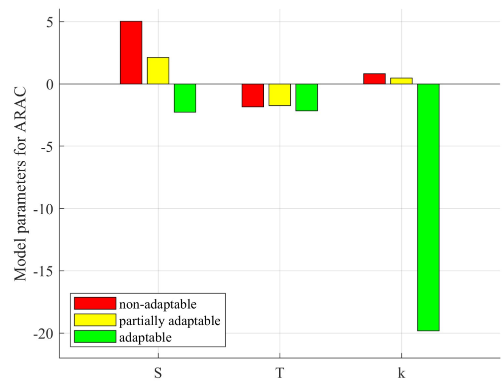

Fig. 5. Linear model parameters for trade-off mechanisms between POF, SLA, and SWG during adaptation to ARAC.

TABLE II. TWO-WAY ANOVA FOR STEP LENGTH, SWING TIME, AND PUSH-OFF FORCES. THE TWO FACTORS ASSESSED WERE THE INTERVENTION TYPE AND THE LEVEL OF ADAPTABILITY.

	Factor(s)		
	Intervention	***Adaptability***	***Intervention* Adaptability***
SLA	$F(1,42) = 43.25$, $p = 5.89e{-}08$	$F(2,42) = 2.36$, $p = 0.107$	$F(2,42) = 1.04$, $p = 0.362$
SWG	$F(1,42) = 54.95$, $p = 3.75e{-}09$	$F(2,42) = 0.55$, $p = 0.581$	$F(2,42) = 0.71$, $p = 0.495$
POF	$F(1,42) = 8.03$, $p = 0.007$	$F(2,42) = 0.32$, $p = 0.727$	$F(2,42) = 0.44$, $p = 0.648$

IV. DISCUSSION

A. *Adaptability to rhythmic cueing*

The significant difference in interlimb gait harmony between SBT and ARAC may be attributed to their dominant adaptation mechanisms or the gait parameter that is targeted by the interventions. A previous study found that control of spatial and temporal features during gait adaptation are independent of each other [19]. Therefore, it is not possible to surmise whether the difference in SSRA between the two interventions was solely due their distinct adaptation mechanisms or due to the gait parameter that was targeted by that intervention, i.e., step length for SBT and step time for ARAC [20, 21].

The relationship in SSRA between SBT and ARAC, shown in Equation (2), reinforces the previously established linear relationship between walking speed and interlimb gait harmony. It also shows that the proprioceptive effects on the subject's gait from the treadmill significantly limited (approximately 26%) the subjects' ability to adapt to the rhythmic cues. This may also be attributed to a multitude of factors, such as a number of cognitive factors that need to remain active to adapt to ARAC compared to SBT, and individual rhythm abilities [7, 22]. To summarize, there are likely limiting effects of the subjects' proprioceptive abilities that may interfere with or enhance their ability to adapt to rhythmic cues on a treadmill setting.

The significant differences in SSRA between adaptability levels show that the disturbance in interlimb harmony is correlated with step velocity. However, the lack of statistically significant correlation with gait parameters suggests the possibility of additional underlying mechanisms among them.

B. *Trade-off mechanisms*

BRK and POF showed a statistically significant correlation with all temporal features during ARAC. However, only POF (and not BRK) was significantly correlated with SLA during adaptation to SBT. This is also consistent with outcomes from previous studies that found augmentation of POF was significantly more effective than BRK at enhancing step length asymmetry during SBT adaptation and post-adaptation [15]. The correlates between either spatial or temporal features with POF were distinct depending on the intervention, possibly owing to their corresponding adaptation mechanisms.

The linear models for trade-off mechanisms in adaptable and non-adaptable subjects were statistically significant for ARAC, but not SBT (Table I). This shows that the trade-offs among SLA, SWG, and POF are linear in nature with rhythmic interventions such as ARAC, but any potential trade-offs within SBT are either insignificant or non-linear. The trade-off mechanisms were personalized to fit the three adaptability levels, which revealed that the models were statistically significant for adaptable and non-adaptable subjects.

The temporal coefficient for adaptable subjects was greater in magnitude than that of non-adaptable subjects, which indicates that a stronger impact is observed in POF for adaptable subjects (compared to non-adaptable) when magnitude of asymmetry in SWG increases. However, the key difference in their trade-off mechanisms was within the relationship of SLA with POF. Non-adaptable subjects showed a positive correlation between SLA and POF, whereas adaptable subjects exhibited a negative linear relationship between the two parameters. It may be inferred that subjects in these two categories exhibited distinct allocation strategies for POF between the spatial and temporal domain.

The primary distinction between subjects classified as adaptable and non-adaptable is the adaptation mechanism that played a more prominent role during adaptation. Non-adaptable subjects had a lower level of engagement with instructional adaptation and higher level of engagement with sensorimotor feedback compared to adaptable subjects.

Although there were no significant differences among adaptability levels in the gait parameters, the strategies in which propulsive forces are allocated to spatial and temporal features were distinctive. Therefore, it may be surmised that orthogonality of changes in step length and swing time could indicate the more dominant adaptation mechanism during training. Understanding of adaptation mechanisms and the way they are reflected in an individual's gait pattern contributes towards a holistic (and targeted) approach towards gait rehabilitation. This would assist therapists to modulate gait interventions that target certain parameters (e.g., step time) and take into consideration "compensation" or "trade-off mechanisms" between different adaptation mechanisms that may impact their rehabilitative progress. A post-stroke subject with unimpaired cognition would benefit more from interventions such as (A)RAC that engage instructive motor learning, whereas someone with cognitive decline may benefit more from interventions like SBT that engage sensorimotor learning methods [28]. The directionality of the trade-off mechanisms may indicate the dominant motor learning process, which would help clinicians determine an optimal intervention type that would maximize the benefits of the individuals.

C. *Limitations and Future Works*

Variability in rhythm abilities between subjects is likely to affect the magnitude of correlation between gait harmony during ARAC and SBT, and the threshold to categorize the three adaptability levels. In addition, the trade-off mechanism model for adaptable subjects during ARAC showed an offset of approximately 20%. This may be attributed to individuals overcoming the proprioceptive impact of the treadmill, or inadequacies within the model regarding additional parameters, such as joint kinematics during gait initiation.

Although the study found a significant correlation between SLA and POF for adaptable subjects during SBT, it does not explain the association between exaggerated propulsion in enhancing adaptive and post-adaptive effects on step length during SBT training [15]. Other studies have found cognitive engagement (e.g., rhythmic auditory or tactile perturbation or using distraction/awareness techniques) during SBT adaptation to improve post-adaptive effects on their gait pattern [13, 23, 26]. A previous study found that braking force was significantly different between planned (anticipated) and unplanned (or sudden) walking contexts, revealing the significant effects of awareness levels [24].

The process(es) of cognitive engagement with retained motor memories remains to be understood in the context of sensorimotor and instructional adaptation mechanisms. Future studies that incorporate such adaptation mechanisms in other contexts (e.g., overground walking with rhythmic cueing or robot-assisted therapy) may elucidate the limitations of these outcomes.

Although partially adaptable subjects exhibited trends in their trade-off mechanisms that were similar to those of non-adaptable subjects, their model was not statistically significant. We suggest a "binary" trade-off mechanism that is based on the direction of changes between spatial and temporal features with respect to propulsive forces. The two possible strategies via which propulsion is allocated between spatial and temporal parameters may be attributed to the dominant adaptation mechanism (sensorimotor or instructional). This would also explain the lack of significance in modeling trade-off mechanisms for the partially adaptable group. For this subject group, both dominant adaptation mechanisms have equal contributions towards gait (a)symmetry, which makes it challenging to identify transient trade-off mechanisms between subjects. Motor adaptation processes are transient and vary in contribution level over different stages of adaptation [25]. Future studies may improve accuracy of their linear models by weighing them according to the type of adaptation mechanism and the training stage, i.e., early and late adaptation.

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