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Using Music to Modify Step-Rate and Running Biomechanics in Healthy Runners

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USING MUSIC TO MODIFY STEP-RATE AND RUNNING BIOMECHANICS IN HEALTHY RUNNERS

by

Erin M. Lally

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ABSTRACT

USING MUSIC TO MODIFY STEP-RATE AND RUNNING BIOMECHANICS IN HEALTHY RUNNERS

by

Erin M. Lally

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Under the Supervision of Professor Jennifer Earl-Boehm

Context: Running-related injury (RRI) is a significant public health issue that may be caused by injurious running biomechanics. Increasing step-rate (SR) using gait retraining may prevent and treat RRI. The Optimizing Performance Through Intrinsic Motivation and Attention for Learning (OPTIMAL) theory indicates enhanced expectancies, autonomy, and external focus of attention will optimize motor learning. Music has been shown to create enhanced expectancies, can provide incidental choices (autonomy), directs attention externally, and may increase compliance. No studies have investigated if music can be used to alter SR and running biomechanics or strategies that may improve compliance to gait retraining.

Objective: The purpose of this study was to 1) compare differences in SR and running biomechanics between those who use music auditory cueing (MUS) and those who use metronome auditory cueing (MET) during the phases of a temporospatial gait retraining protocol, 2) compare differences in RPE change scores across four temporospatial gait retraining sessions between the MUS and MET group, and 3) determine if there is an association between groups (MUS and MET) and compliance to a self-administered, temporospatial gait retraining protocol and describe the likelihood of compliance between groups (MUS and MET).

Methods: Thirty, healthy recreational runners were included and randomly placed in either the MET or MUS group. Inertial measurement unit motion analysis collected SR, peak positive tibial acceleration (PPA), and peak stance phase hip adduction (peakHIPADD) during the stance phase of running. A cellular device application collected running volume and SR data when participants ran outside of the lab, which defined compliance. The Borg's rate of perceived exertion (RPE) scale was used to compare change in RPE between groups. A multivariate repeated measures ANOVA was used to compare SR, PPA, and peakHIPADD from the introductory pretest (INTROpre) and the three posttests (INTROpost, LABpost, SELFpost). Change scores between baseline RPE and RPE after each gait retraining session were calculated and analyzed using a mixed repeated measures ANOVA. SR and running volume were derived from the cellular application exports and compliance was defined as 1) maintaining an average SR within +/- two steps per minute of the target SR throughout each run and 2) maintaining the average running volume. Runners were assigned as "compliant" and "noncompliant". A Fischer's exact test was performed, and an odds ratio was calculated to determine association and likelihood of compliance between groups.

Results: Both groups increased SR between the INTROpre and introductory posttest (INTROpost) ($p < .001$), and the increase in SR was maintained at all other posttest timepoints (LABpost and SELFpost). There were no differences in PPA or peakHIPADD at any posttest timepoints regardless of group. No significant differences in RPE change scores between groups across time were found. There was a significant association between group and compliance ($p = .05$) and the MUS group was ~6 times as likely to comply with the self-administered gait retraining program.

Conclusions: SR can be altered using either a metronome or music tempo. Both a metronome and music can be used as an auditory cue without creating increased perception of exertion. Runners using the music auditory cueing may continue to practice their new target SR more than runners assigned a metronome cueing, which provides rationale to use music to retrain SR within a self-administered gait retraining protocol. Running biomechanics may not have changed since SR was only increased by 5% so future research should repeat the current study methods using larger increases in SR.

To myself for all the times I wasn’t sure I could and continued anyway.
For my mom and dad who started it all.
To my family, especially Grandma Cozzi, Michael, Betsy, and Amelia, and my friends who always understood why I couldn’t make it.
& To Chris, my biggest motivation, who this simply would not be possible without.

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LIST OF ABBREVIATIONS

RRI	Running-related injury
VLR	Vertical loading rate
SR	Step-rate
OPTIMAL	Optimizing Performance Through Intrinsic Motivation and Attention for Learning
RPE	Rate of perceived exertion
PPA	Peak tibial positive acceleration
peakHIPADD	Peak stance phase hip adduction
IMU	Inertial measurement unit
Spm	Steps per minute
PFP	Patellofemoral pain
EMTP	Exertional medial tibial pain
ITB	Iliotibial band
vGRF	Vertical ground reaction force
EMG	electromyographic
3D	Three-dimensional
LE	Lower extremity
RFS	Rear foot strike
MFS	Midfoot strike
FFS	Forefoot strike
MET	Metronome group
MUS	Music group
Introductory pretest	INTROpre

Introductory posttest	INTROpost
In-lab gait retraining posttest	LAB post
Self-administered gait retraining posttest	SELFpost
IC	Initial contact
TO	Toe-off
SRWEAV	Step-rate from Weav app data
RVWeav	Running volume from Weav app data

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Figure 3: OPTIMAL Theory Schematic was produced from Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning, Wulf G, Lewthwaite R. 2016;23(5):1382-1414 with permission from Springer Nature and Copyright Clearance Center.

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Chapter 1: Introduction

Running is an accessible form of physical activity that accompanies many health-related benefits.[1] Unfortunately, there is high risk for runners to develop a running-related injury (RRI)[2,3] and incurring a RRI is one of the major barriers to continuing to run,[4] depriving individuals of the many health benefits associated with running. RRI can be defined as musculoskeletal pain in the lower limbs that causes an individual to limit or stop running for at least 7 days or 3 consecutive scheduled training sessions, or to seek a consultation from a health care professional.[5] RRI consequences can include financial cost, (≥ 75$ per RRI),[6,7] long times until recovery (1 to 5 months),[8] and high reoccurrence rates (up to 70% of all cases).[9] RRIs are observed at high rates in novice and recreational runners,[3] habitual and experienced runners,[10,11] and military personnel.[12,13]

Development of RRI is certainly multifactorial,[14] however, running biomechanics may be a major contributor to RRI.[15-20] Running biomechanics linked to RRI include increased vertical loading rate (VLR),[18,20-22] and excessive hip adduction.[15,18,23,24] Many researchers have applied interventions such as strength training programs[25-27] to attempt to correct potentially harmful running biomechanics. However, the theory that increased strength will create change to running biomechanics has been disproven through the work of several studies.[25-27] It is likely that the lack of kinematic change after improved strength may be due to the inclination humans have to maintain usual movement patterns.[26] Therefore, motor learning interventions, such as gait retraining, may be a more effective strategy when aiming to alter movement patterns.[28] Gait retraining is a specific motor learning intervention aimed to re-educate a faulty component of gait[28-30] and is recommended to address faulty running biomechanics.[30-34] Temporospatial gait retraining entails a manipulation of temporospatial characteristics of gait, like step-rate (SR).

Lower SR has been directly related to increased risk of sustaining a RRI[35] and increasing SR has led to decreases in loading rate,[30,36] and injurious hip and knee kinematics and kinetics.[30,32] When an individual attempts to increase their SR, motor learning must take place before the new SR is permanently adopted,[37] but few temporospatial gait retraining protocols call upon motor learning theory. Potentially, outcomes of temporospatial gait retraining protocols can be further improved when they are designed according to motor learning theory.

The Optimizing Performance Through Intrinsic Motivation and Attention for Learning (OPTIMAL) theory[38] identifies three elements important to optimizing motor learning including: 1) enhanced expectancies, 2) autonomy, and 3) external focus of attention. When a researcher or clinician designs an intervention with these three elements at the forefront, motor learning outcomes will likely improve.[38] Enhanced expectancies refer to the positive expectations of upcoming performance on a task. Examples of constructs that may operationally define enhanced expectancies include but are not limited to improved self-confidence,[39] increased self-efficacy,[40] positive affect (emotions, mood),[41] and decreased perceived exertion.[42] Autonomy is having the ability to control one's actions.[43] Attentional focus is the information at which the performer's attention, or consciousness, is directed.[37] External focus directs the attention of the learner to the consequence of the motion, rather than within the body.[37] Temporospatial gait retraining has primarily been accomplished using the auditory cue of a metronome. Drawing an individual's focus to a metronome may be considered an external focus. However, external focus of attention, enhanced expectancies, and autonomy independently contribute to improved motor learning and are most effective when all three elements are included.[44,45] While a metronome is an external focus cue and is effective to improve potentially harmful biomechanics, there are not known enhanced expectancies or autonomy associated with this strategy. Successful outcomes of temporospatial gait retraining protocols used in the literature may be further improved by catering to enhanced expectancies and autonomy, as well.

Within the literature, there are reports that increasing SR using a metronome can increase ratings of perceived exertion (RPE), which can be conceptualized as a negative expectancy.[32] Also, many runners prefer to listen to music when they run[46] and foreknowledge of the removal of music is theorized to impact the typical ability to perform an exercise.[47] Thus, removing music from an activity, may create negative expectancies and negatively impact motor learning. Music has been shown to create positive affect,[48-52] distract exercisers from discomfort,[53] and alleviate perceptions of exertion during exercise.[42,54-57] Importantly, there is evidence that synchronization of SR can be easily accomplished using music tempo.[54,58] Synchronous music is a mode of delivering music in which the individual is instructed to synchronize movements to the tempo of a song.[57] Evidence indicates that runners respond to musical rhythm by synchronizing their SR without even being told to do so.[59,60] Additionally, specific advantages of synchronous music include neurological responses that optimize motor control, sensory perception, and attention,[61] all of which contribute to the motor learning process.[37] Synchronous music has also been shown to be a superior choice to enhance expectancies over asynchronous music.[48,50,62] The benefits that music has been found to create can be used to enhance expectancies and synchronizing SR to music tempo is feasible for temporospatial gait retraining protocols.

When autonomous practice conditions are emphasized there is evidence of promoted error processing,[63] which is especially important to motor learning. Musical effects on exercise are based on personal[56,57,64,65] and situational factors,[56,57,66-69] the qualities of music,[70-74] and an individual's experiences surrounding the music.[71] Due to the very individualistic antecedents to music preference, it is suggested that self-selected music be used in research to ensure the motivational qualities of the music are specific to that individual.[56,57] When incidental choices, such as music playlist selection, are offered to learners during temporospatial gait retraining protocols, autonomous practice conditions are created and will likely increase motor learning outcomes.[38]

The OPTIMAL theory also posits that successful outcomes of motor learning will enhance motivation to engage in practice of the new skill in a meaningful way.[38] When considering movement training, ensuring compliance and/or adherence to practicing the skill is of the utmost importance to motor learning and retention.[37,75] Compliance has been defined as "the extent to which the patient's behavior matches the prescriber's recommendations".[76] Lack of compliance to exercise programs may occur when the prescription ignores the psychosocial needs of an individual when designing exercise programs[77] or when the person doesn't enjoy the activity.[78] The enhanced expectancies and autonomy experienced during exercising to self-selected music (improved performance, motor coordination, and positive feelings) likely lead to increased motivation for practice[38,39,79,80] and increased adherence to the activity.[55] Although compliance is more passive engagement in prescribed programs when compared to adherence, it is possible that compliance to temporospatial gait retraining can be improved when music is used. To my knowledge, no studies have specifically investigated if using music in temporospatial gait retraining can improve compliance.

One drawback of gait retraining interventions is the lack of access to techniques outside of the lab environment and the large time commitment. Studies have performed allowed self-administration of temporospatial-focused gait retraining with minimal time required by the researcher.[30,81] The technology used for self-administered gait retraining has produced favorable biomechanical changes but may still cost the runner upwards of 300.00 dollars. However, ~85%

of Americans already own cell phones.[82] Running is one of the most accessible forms of physical activity,[1] but gait retraining techniques are not equally as accessible. To effectively prevent and treat RRI with gait retraining, more accessible ways, including using mobile-monitoring and/or phone applications to administer temporospatial gait retraining should be explored.

Summary of the problem: Few studies have grounded their gait retraining intervention design within a theory of motor learning, which may leave researchers to question whether the already successful outcomes of gait retraining can be further improved. The OPTIMAL theory indicates enhanced expectancies, autonomy, and external focus of attention will optimize motor learning[38] and inclusion of all three of these elements is a superior approach when designing interventions. [44,45] Music has been shown to create enhanced expectancies,[42,48-57] can provide incidental choices (autonomy), both of which may increase compliance, [38,39,79,80] and directs attention externally. Experts have indicated they encourage the use of music or would much rather use music to increase SR,[83] however, there is currently no comprehensive study to indicate that positive changes in running biomechanics can be acquired, learned, or retained when using music in a temporospatial gait retraining protocol. Before using music as a means to increase SR in temporospatial gait retraining, it is imperative to determine if increased SR elicited by synchronous music also creates the desired changes in running biomechanics that are essential to prevent and treat RRI. One drawback of gait retraining interventions is the large time commitment that may not be realistic for many clinical settings. Additionally, there are methods that may better integrate gait retraining into a variety of settings and alter this intervention to fit the needs of runners. Temporospatial gait retraining has been completed using self-administration techniques, but few studies have utilized the highly accessible cell phone technology available. Additionally, no studies have investigated strategies that may improve compliance, such as the use of synchronous music, to self-administered gait retraining protocols even though compliance to practice is of great importance to motor learning and retention. Further exploration of self-administered gait retraining compliance can determine the impact current methods and synchronous music have on compliance, which informs the clinical utility of gait retraining.

Purpose Statement:

The purpose of this study was to 1) determine if differences exist in running biomechanics between those who receive temporospatial gait retraining using synchronous music (MUS group) and those who receive temporospatial gait retraining using a metronome (MET group), 2) determine differences in ratings of perceived exertion between the MUS and MET group, and 3) investigate compliance to temporospatial gait retraining between the MUS and MET group.

Operational Definitions:

- Running biomechanics: SR, peak positive tibial acceleration (PPA), and peak hip adduction joint angle during the stance phase of running (peakHIPADD) derived from inertial measurement units (IMU).
- Temporospatial gait retraining: Increasing SR during running by 5% above preferred SR using auditory and verbal cueing. Phases of the temporospatial gait retraining will be defined as the following time points: introductory pretest (INTROpre), introductory posttest (INTROpost), in-lab gait retraining posttest (LABpost), self-administered gait retraining posttest (SELFpost).

- Synchronous music: delivery of music in which the individual is instructed to synchronize running SR to the tempo of a song, which is altered to the target SR of 5% above preferred SR.
- Perceived exertion: the degree of heaviness and strain experienced in physical work as estimated according to the Borg's RPE scale.
- Compliance: the extent to which the participant's behavior matches the researcher's requests, specifically, maintaining an average SR within +/- two steps per minute of the target SR throughout each run and average weekly running volume recorded prior to the study.

Specific Aims

Aim 1: Compare differences in SR and running biomechanics between the MUS and MET group during the phases of a temporospatial gait retraining protocol (INTROpre, INTROpost, LABpost, SELFpost).

Hypothesis 1a: It was hypothesized there would be a significant interaction between group and time where differences in SR between timepoints depended on group. Further follow up tests examining the differences between the INTROpre and the INTROpost and between the INTROpost and subsequent posttest timepoints (LABpost, SELFpost) separately for each group (MUS, MET) were expected to reveal the MUS group SR significantly increased from INTROpre to INTROpost and did not significantly change from the INTROpost to LABpost or SELFpost timepoints. It was also expected that the MET group SR significantly increased from INTROpre to INTROpost and did not significantly change from INTROpost to LABpost but decreased from the INTROpost to at the SELFpost timepoint.

Hypothesis 1b: It was hypothesized there would be a significant interaction between group and time where differences in PPA between timepoints depended on group. Further follow up tests examining the differences between the INTROpre and the INTROpost and between the INTROpost and subsequent posttest timepoints (LABpost, SELFpost) separately for each group (MUS, MET) were expected to reveal the MUS group PPA significantly decreased from INTROpre to INTROpost and did not significantly change from the INTROpost to LABpost or SELFpost timepoints. It was also expected that the MET group PPA significantly decreased from INTROpre to INTROpost and did not significantly change from INTROpost to LABpost but increased from the INTROpost to at the SELFpost timepoint.

Hypothesis 1c. It was hypothesized there would be a significant interaction between group and time where differences in peakHIPADD between timepoints depended on group. Further follow up tests examining the differences between the INTROpre and the INTROpost and between the INTROpost and subsequent posttest timepoints (LABpost, SELFpost) separately for each group (MUS, MET) were expected to reveal the MUS group peakHIPADD significantly decreased from INTROpre to INTROpost and did not significantly change from the INTROpost to LABpost or SELFpost timepoints. It was also expected that the MET group peakHIPADD significantly decreased from INTROpre to INTROpost and did not significantly change from INTROpost to LABpost but increased from the INTROpost to at the SELFpost timepoint.

Aim 2: Compare differences in RPE change scores across four temporospatial gait retraining sessions between the MUS and MET group.

Hypothesis 2: There would be a main effect of group for RPE change scores. Follow up tests (simple main effects examination) would reveal RPE change score was larger and in the positive direction (greater perceived exertion) in the MET group when compared to the MUS group, regardless of time point.

Aim 3: Determine if there is an association between groups (MUS and MET) and compliance to a self-administered, temporospatial gait retraining protocol and describe the likelihood of compliance between groups (MUS and MET).

Hypothesis 3a: There would be an association between the type of gait retraining form (MUS and MET) and compliance.

Hypothesis 3b: Those in the MUS group would demonstrate higher likelihood of compliance when compared to those in the MET group.

Delimitations:

This study chose to focus on recreational runners aged 18-40 years who maintain an average weekly running mileage of 8km or greater in hopes to capture recreational runners that consistently run, perhaps putting them at risk for RRI, but do not maintain high average mileage. Recruitment for this study took place in the Milwaukee community, on the University of Wisconsin-Milwaukee campus, businesses in which recreational runners may frequent, and minority owned and other Milwaukee community exercise facilities. I chose to use technology that requires access to an iPhone or iPod for this study due to the data that can be collected and provide insight into the research from this technology. Compared to other technologies used in the literature, an iPhone is more likely to be owned by various individuals in the community. The biomechanical variables were intentionally collected with an IMU system on a treadmill instead of a force plate during overground running due to the need for continuous running required for the intervention. PPA is a common surrogate for force variables and treadmill running has been found to be comparable to overground running when considering kinematic and kinetic variables. The variables of interest within this study did not account for all the variables that may influence or define motor learning, running biomechanics, and perceptions of exertion.

Assumptions:

Participants in this study were asked to self-report their RPE levels and it is assumed they will only give their honest responses. Some participants in this study self-selected music they would enjoy running to and it was assumed that they made honest selections. It was assumed that the participants intended to comply with the temporospatial gait retraining during all phases of the study when consenting to participate in the study.

Limitations:

Shoe wear, running participation, and feedback time were not directly controlled for during the phases of the study in attempt to maintain a more integrated experience of the participants and how they choose to partake in running and will be considered during the dissemination of results. Self-administration and overtime periods exist within the study design and may cause lack of contrition to the study. Techniques were inserted into the study to ensure that the data needed for the study is received. The generalizability of the results of this study is limited to non-injured recreational runners. There was no “true” control group for this study, which can be considered a limitation. However, use of a metronome is currently the only other auditory cue that has been used to accomplish temporospatial gait retraining and is, therefore, an acceptable reference group for the purposes of this study. Finally, the OPTIMAL theory recommends interventions create autonomy, enhanced expectancies, and external focus of attention. This study only adopted a few strategies that best relate to music, running, and gait retraining. I acknowledge that this study did not measure autonomy, external focus of attention, or goal-action coupling. However, to adhere to the OPTIMAL theory, researchers and clinicians do not have to use all techniques shown to be effective to produce superior motor performance and motor learning outcomes. Also, the evidence strongly supports the strategies being used in this study will lead to increased autonomy, external focus of attention, and goal-action coupling.

Chapter Two: Literature Review

This literature review provides the background and rationale for running gait retraining interventions as a prevention and/or rehabilitation approach to RRI. A brief review of the conceptual framework by Bertelson et al.[14] describing RRI etiology will provide evidence indicating running biomechanics are a main underlying mechanism for RRI through. Since gait retraining is a form of motor learning, or relearning, the OPTIMAL theory[38] will be explained and examined, particularly in the context of how it can be applied to gait retraining. Existing evidence on the effects of music in exercise and sport will demonstrate that using music can, according to the OPTIMAL theory, enhance motor learning and should be explored further. The limitations of the OPTIMAL theory will be highlighted, as well. Finally, the common method designs used within the gait retraining literature and their limitations will be discussed. Techniques of gait retraining, including 1) kinematic, 2) kinetic, 3) temporospatial, 4) in-field, and 4) comparative gait retraining studies along with limitations and knowledge gaps of each will be another main focus of this review. Compliance to exercise and gait retraining will be synthesized to further illustrate the rationale for the use of music as a gait retraining technique.

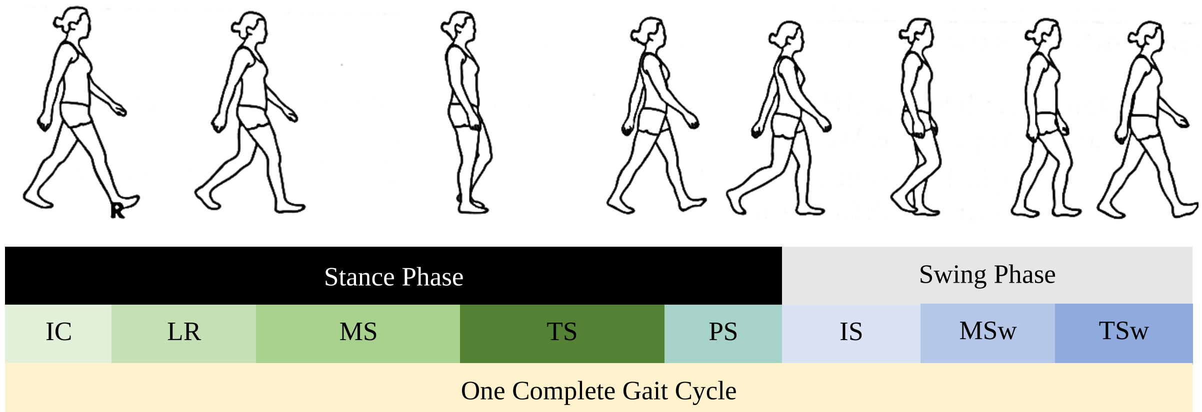
Why Runners?

Running is arguably one of the most accessible forms of physical activity.[1] However, there is high risk for runners to develop a RRI.[2,3] The burden of RRI includes significant healthcare expenses (≥ 75$ per RRI), [6,7] long recovery times ranging from 1 to 5 months,[8] and high reoccurrence rates (up to 70% of all cases).[9] Furthermore, incurring a RRI has been shown as one of the major barriers to continuing to run,[4] which deprives individuals of the many health benefits associated with running. RRI is common and threatens the health of many populations including novice and recreational runners,[3] habitual and experienced runners, [10,11] and military personnel.[12,13]

Running and Running-related Injury Definitions and Etiological Framework

Running Gait Cycle: Describing the phases of the gait cycle is essential to orient researchers and clinicians to the biomechanical processes that occur when an individual runs and the language typically used in the RRI literature. Running is typically viewed within gait cycles. To understand the subsequent sections of this literature review, it is first important to understand the components of the gait cycle. Figure 1 depicts the full gait cycle where the reference limb is the right limb. Stance phase is the period in the gait cycle when the reference limb foot is in contact with the ground. Initial contact is defined as the instant the reference foot contacts the ground. Loading response occurs when weight begins to transfer to the reference limb in contact with the ground with a simultaneous unloading of the contralateral limb. Midstance and terminal stance is characterized by having only the reference foot in contact with the ground while the contralateral limb is airborne. Midstance and terminal stance are commonly referred to as "single-limb support" periods of the gait cycle and are characterized by the center of mass progressing forward to propel an individual. Pre-swing phase is when the reference limb is being unloaded and ultimately toeing-off. During pre-swing, weight is transferred to the contralateral limb as this limb begins initial contact. Toe off occurs when the reference limb foot is lifted off the ground and the individual will then enter swing phase. Swing phase is occurring as the reference limb now becomes airborne. Initial swing, midswing, and terminal swing all occur throughout the swing phase as the airborne limb advances forward to prepare for another initial contact.[84]

Figure 1. *The gait cycle of the right limb*[84]



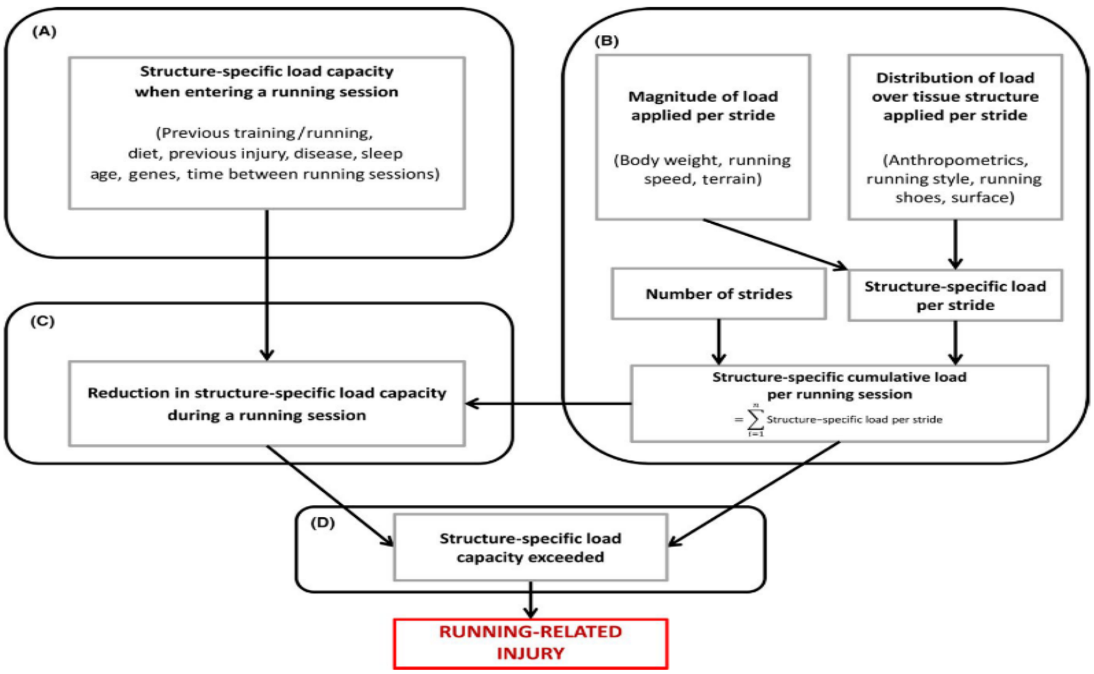
IC, initial contact; LR, loading response; MS, midstance; TS, terminal stance; PS, pre-swing; IS, initial swing; MSw, mid-swing; TSw, terminal swing

Each time these phases are completed, it is referred to as one gait cycle. Gait cycles are measured in units called running strides. A running stride is completed when there have been two successive contacts of the same foot.[84] In other words, a stride is taken when the right heel contacts the ground and then contacts the ground again. Understanding of a running stride is relevant to understand the conceptual framework[14] being used in this study. A few other definitions relevant to understanding the anatomy of a gait cycle are running step and running SR, also sometimes referred to as cadence. A running step is essentially half a stride and is completed when both limbs have contacted the ground. Specifically, one step is taken by the runner when both their right heel contacts the ground and then the left heel contacts the ground. Runners also have a very specific rate at which they complete a step. SR is defined as the frequency at which an individual takes one step (right and left foot contact the ground). SR is typically measured in steps per minute (spm). Knowledge of a running step and running SR will be very relevant to this study.

RRI Definition: Researchers have identified that the definition of a RRI within the literature has varied.[2,11,85] To help salvage this inconsistency and lead to more accurate depictions of RRI, Yamato et al.[5] conducted a modified Delphi study. The authors used a thorough process to create a standard definition for RRI based on expert (38 individuals from nine different countries) consensus. This study is the first to use such a rigorous process to define RRI, and the expert consensus definition is: "musculoskeletal pain in the lower limbs that causes a restriction on or stoppage of running (distance, speed, duration, or training) for at least 7 days or 3 consecutive scheduled training sessions, or that requires the runner to consult a physician or other health professional". Several musculoskeletal injuries are frequently associated with the activity of running. RRI encompasses many diagnoses, including but not limited to patellofemoral pain (PFP), exertional medial tibial pain (EMTP), and iliotibial band (ITB) pathology.[2]

RRI etiological framework: Due to the commonality of RRI plenty of research has been dedicated to discovering elements that may influence pathological loading during running. In recent years, Bertelsen et. al.[14] proposed a conceptual model to organize the literature on the etiology of RRI. The model describes how biological factors interact to influence tissue overload and RRI. (Figure 1) Pretraining variables within (Figure 1, Box A) decrease the load capacity of tissue. Training related variables (Figure 1, Box B) increase cumulative load applied during training. Injury occurs when there is a reduction in load capacity of the musculoskeletal tissue (Figure 1, Box C) that is overcome by the applied load (Figure 1, Box B). Injury may also occur when the load capacity of the musculoskeletal tissue is not reduced but is overcome by an increased applied load. In the simplest terms, RRI occurs when internal resistance to load of musculoskeletal tissue is overcome by the external load applied to the tissue, resulting in damage.[14] The benefits of this model are that it was developed to encourage researchers and clinicians to view RRI cause in a wider lens and to consider RRI risk on a multi-factorial spectrum.[14] For instance, individuals may display non-modifiable characteristics, such as history of injury that place them at a greater risk for RRI before entering a running session (Figure 1, Box A). Additionally, researchers can use this model to examine causal variables and account for confounding variables when conducting research on RRI. However, other variables within the model (Figure 1, Box B) may be modifiable and can be addressed to mitigate the increased risk.

Figure 2. *RRI etiology model*[14]



Running biomechanics: Studies indicate running biomechanics are modifiable factors within the RRI etiology model,[86-88] thus, these factors will be explained further in this review. Running style (Figure 2, Box B) is the terminology used within the model,[14] however, running biomechanics is a more specific title for kinematic and kinetic variables. Kinematics are most commonly quantified by angles of the joints during an activity. The hip, knee, and ankle joint kinematics are of interest when investigating running biomechanics in the context of RRI. Kinetics are quantified by load variables, such as joint moments, acceleration measures, and energy absorption variables. There is largely, retrospective, conflicting evidence on running kinematics and kinetics that are injurious when it comes to RRI.[89,90] However, some of the most recognized injurious running biomechanics are increased (VLR),[18-22,91,92] decreased knee flexion,[15,93,94] and excessive hip adduction.[15,18,23,24,95] Tissue capacity is thought to be more easily overcome when movement deviations and/or excessive loading rates are exhibited during running.[14]

VLR is considered the rate of increase in vertical ground reaction force (vGRF) during a foot contact with the ground. VLR is typically calculated within the first 20-80% of the period between contact and peak impact of the gait cycle and is numerically represented as the change in force (expressed in Newtons) divided by the time (expressed in seconds).[18,22] In theory, an increased VLR is indicative of an increased external load applied to the body because 1) magnitude of force is higher, 2) time to absorb force is less, or 3) both magnitude of force is higher, and this force is absorbed in a short amount of time.[96] Many studies have found a relationship with VLR and tibial stress fracture,[22] plantar fasciitis,[19,92] and PFP.[92] Prospective studies support increased VLR is predictive of general RRI.[97] Some studies have not discovered VLR to influence RRI.[98,99] Even with some conflicting evidence, VLR is the most consistent vGRF variable to show a relationship to injury.[18,22,92,97] It is for this reason that reducing VLR should be an outcome of interventions to prevent and treat RRI. PPA has shown high correlations to VLR during running[100-102] and PPA has evidence of a relationship to increased RRI,[103] as well. The added benefit of PPA versus VLR is the ability to mount accelerometers on the runner while they continuously run, which is not possible when using a force plate.

Decreased knee flexion would clinically present as a straighter knee throughout the gait cycle, specifically in stance phase.[104] It is speculated that decreased knee flexion during running interrupts the distribution of load as, during initial phases of gait, greater knee flexion, or larger displacement, facilitates more gradual load absorption.[105] Currently, evidence is conflicting on whether decreased knee flexion is associated directly with RRI.[24,93,94,106] Conflicting results may be due to the diagnostic entities of RRI. Each RRI diagnosis may have slightly different pathomechanics, which may come with differences in kinematic presentation. Still, smaller knee flexion angles are indicative of increased knee joint stiffness,[107] which has been prospectively shown to predict RRI.[108] Therefore, it may be beneficial for clinicians to consider decreased knee flexion as potentially harmful and attempt to address it in runners.

Increased hip adduction is commonly observed through collapsed knees presenting as less space between the knees during running.[104] Frontal plane deviations, such as increased hip adduction, has been shown to alter the distribution of loading within the LE,[17,109,110] leaving specific aspects of the musculoskeletal system vulnerable to excessive loading. Primarily those with a PFP[15,23] and EMTP[15,18,95] display greater hip adduction. From a theoretical perspective, increased hip adduction has been shown to increase PFJ stress[17,110] experienced during running and also increase medial stress on the tibia during running.[109] There is literature to support that increased hip adduction may impact distribution of loading throughout running, and therefore, increase risk of RRI.

The RRI etiology model indicates RRI development is multifactorial. Therefore, it is unfair to say that one factor in the RRI etiological model is the “best” way to prevent or treat RRI. In fact, this model was developed to display the broad scope of potential variables that may be a place to start with each individual runner, as no two runners will be exactly the same.[14] However, through this review of the literature, running biomechanics are a commonly cited underpinning to mechanism of RRI.[111-118] Of course, running kinematics and kinetics are not the only factor related to RRI, but many of the variables included in the etiological model are underpinned by the theory that how the person runs is a key mediator to injury development. Investigating strategies to change running biomechanics may be one of the most compelling avenues, according to the literature. Researchers have also recognized this area of expansion and thus, several interventions have been studied to attempt to change running biomechanics.

Interventions to Change Running Biomechanics:

Since running biomechanics are the hypothesized underlying mechanism for increased risk of RRI, alteration of biomechanics has been explored. Researchers have implied that strength training programs have the capacity to decrease RRI incidence[119] but contrary results have been reported.[120] Theoretically, muscles with greater strength will contract to create more force, keep joints in more neutral positions, and absorb more load as an individual does an activity. For example, when someone has "strong" hip abductors and external rotators, these muscles would keep the hip joint in less adducted or internally rotated positions while running. Interestingly, studies have shown that hip strength were generally not related to joint movements during running.[121,122] The lack of relationship between strength and movement of the hip during running leaves researchers and clinicians questioning this theory. Earlier research has been dedicated to changing running biomechanics by strengthening muscles that control knee and hip movements.[25-27] However, it appears that strength training in isolation may not provide a strong basis for changing biomechanics long-term.

Willy et al.[27] discovered a six-week progressive hip abductor and external rotator strength program did improve strength, however, there were no changes to hip running biomechanics. Similar results were reported of Earl and Hoch[25] in that an eight week, proximally focused strength training intervention did not improve kinematics of the hip and knee, but kinetics were.

Perhaps this suggests that increased strength of hip muscles does positively impact kinetics during running but does not necessarily change kinematics.[25] In a study conducted by Snyder et al.[26] only small kinematic changes were noted after a strength training program, as well. The authors hypothesized that the small kinematic changes despite larger kinetic changes and improved muscular strength may be due to the inclination to maintain usual movement patterns. Results of Bazett-Jones et al.[123] also demonstrated that an exhaustive run brought about decreases in strength in runners, but not altered kinematics. Therefore, it is perfectly plausible that kinematics during running are less related to decreased muscle strength. These pioneering investigations have led to the discovery that strength training may improve the capacity for muscle force production but changes in movement do not appear to occur with strengthening alone.

Since strength interventions alone are not effective to alter running biomechanics, gait retraining has been suggested within the sport medicine community. Gait retraining is the systematic re-education of a faulty component of gait,[29,30] which may include running kinematics, kinetics, and temporospatial variables. Kinematic gait retraining would consist of cueing to bring about specific changes to a joint angle.[28] Kinetic gait retraining would consist of cueing to bring about a change in the magnitude of loading, otherwise known as impact. Temporospatial gait retraining would be focused on changing stride length or SR, to alter both kinematics and kinetics. Regardless of the gait retraining movement goal, gait retraining is motor learning. Principles of traditional motor learning theory have guided gait retraining studies. The next section will review traditional motor learning and the limitations that may accompany using more traditional principles in interventions according to emerging evidence.

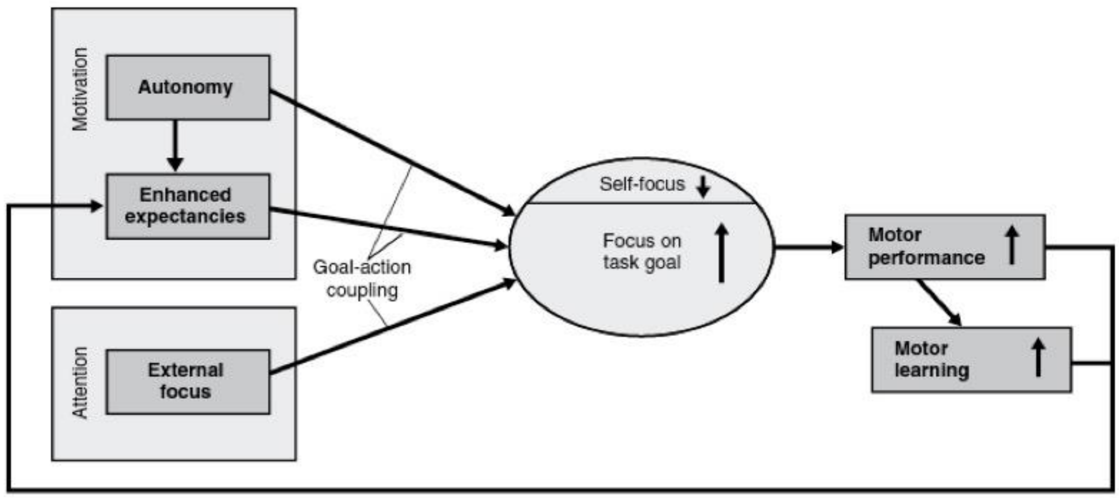
Traditional Motor Learning Theory:

Historically, motor learning experts viewed the motor learning process as a more "computer processing" experience. It was thought that tough experiences would enhance motor learning, so motor learning interventions were specifically designed to be more difficult and require more effort for the new learner.[124-126] Recent evidence now suggests that difficult practice conditions may hinder motor performance and motor learning and highlights the process of motor learning for humans is not comparable to a computer.[38] For example, motor behavior (e.g. recreational running or rehabilitation) is observed in a social context. The cognitions that take place during motor learning are ever-present, as well. All the social and cognitive elements humans experience, as well as the new task itself, must be acknowledged when explaining the motor learning process. For all these reasons, the OPTIMAL theory[38] was proposed and is currently the most all-encompassing theory available to use when designing an intervention specific to motor-learning.

The OPTIMAL Theory of Motor Learning:

The OPTIMAL theory was developed in hopes to guide researchers and clinicians in more effective motor learning intervention based on the recent evidence.[38] In addition to effectiveness, the OPTIMAL theory considers several different scientific perspectives of motor learning theory and create a more coherent foundation for the development of motor learning intervention for both researchers and clinicians.[38] As a result, the OPTIMAL theory accounts for evidence-based updates including but not limited to neuroscience and sport psychology that were called for from the motor learning intervention discipline.[38] The OPTIMAL theory is the first to touch on the importance of both behavioral and motivational influences on motor learning and motor performance.[38] The OPTIMAL theory acknowledges that motor behavior is a form of human behavior and thus motor learning theory must encompass the social-cognitive-affective-motor elements of motor behavior.[38]

Figure 3. *OPTIMAL Theory Schematic*[38]



Motor performance: Any new skill can be classified on a spectrum. A motor skill is a skill in which the primary determinant of movement success is the quality of the movement itself rather than the decision-making aspects of the task.[37] A cognitive skill depends more on strategy than on the production of movement itself.[37] If running was defined as a purely motor skill, the primary goal would be to produce movements that maximize performance (personal best times or longest mileage). If we were to view running as purely a cognitive skill, the primary goal would focus more on the strategy of running rather than performance exhibited during the run. It is very rare that one skill is ever purely motor or purely cognitive.[37] Most skills, including running, can be classified as motor-cognitive skills where the full execution of the skill is knowing what to do (cognitive aspects) and how to execute the motion (motor aspects).[37]

When a motor-cognitive skill is continuous, such as running, a closed-loop control process is initiated.[37] First, input will be detected by the individual about to run. Input is an external stimulus that is interpreted and responded to accordingly during movement.[37] Input may be something seen (visual) or heard (auditory) in the environment. Input may also be augmented (verbal), like coaching instruction, or sensory, like proprioception from the musculoskeletal system. Several types of input being received are then interpreted by the individual, which is the cognitive portion of skill initiation.[37] Next, a motor program from the brain is transmitted to the spinal cord and commands the relevant muscles to execute the desired movement, which is the motor portion of skill initiation.[37] A motor program is a set of motor commands that is pre-structured at the executive level and that defines the essential details of a skilled action.[37] The closed-loop control process can be illustrated with a running example. It is suggested that a runner would already have a set generalized motor program stored to initiate running.[127] While the runner initiates this general running motor program, various input will be received simultaneously while the individual cognitively determines what to do with the input. This closed-loop control process will continuously occur throughout the movement.[37]

Every time someone attempts a new skill, they must motor perform. Motor performance is the observable production of the skill. Measures of motor performance within gait retraining would be 1) changing joint angles 2) altering loading, 3) altering SR or stride length.

Motor learning: A motor program will not performed without attention or unconsciously (automatically), until it is learned. Motor learning is defined as the capacity for producing a particular movement and includes practice or experience leading to relatively permanent changes to motor skills.[37] Although motor learning is not directly observable, researchers can assume learning processes are occurring based on observing the consistency change in motor performance of the new skill.[128] Some theoretical depictions of motor learning during gait retraining protocols are observation of the new target gait pattern being executed 1) autonomously, 2) automatically, 3) accurately, and 4) consistently. There are a few key phases of skill-learning that guide researchers and clinicians in facilitating the motor-learning process.

Phases of Motor Learning (Table 1): Acquisition is the first phase to motor learning and is characterized by the individual successfully being able to perform the desired skill.[37] Acquisition of the new skill may be noted when there is accuracy in executing the skill. Acquisition of the new task is often accompanied by the need to receive instructions about what the new task is.[129] Individuals spend a majority of the acquisition phase talking to themselves about what to do and thinking about strategies that will work.[130] During acquisition, attention is placed on the input being received and the cognitive processes to execute the movement[130-134] often accompanied with error or inaccuracy.[37] Instruction and feedback from the researcher or clinician are beneficial during this phase.[37] The largest gains in the desired change are likely observed in the acquisition phase.[130] As the learner becomes more experienced with the task, the cognitive processes of performing the skill tend to drop out.[37] The amount of time the acquisition phase takes depends on the complexity of the task and the clarity of the instructions being given.[37]

The second phase is the “learning” of the new skill. At the start of the learning phase, the individual may still be relying on the visual or cognitive areas of the brain to perform the new task, however, the learner’s attention is shifted to optimizing the new movement and adjusting the motor program[37,130,135] and they then become less reliant on input.[130,134,136,137] During the learning phase, the individual gradually requires less instruction, and the new task becomes more automatic.[130] For this reason, instruction during this phase become less important.[37] Improvements are less noticeable during the learning phase when compared to the acquisition phase but may present as consistency performing the new task accurately with less effort having to be put forth when compared to the acquisition phase.[37,130]

The final phase in the motor learning process is retention of the newly learned motor pattern. Retention describes when an individual can maintain the new desired movement pattern after time has passed with no clinician-guided practice.[37] Often the retention of a task is called automatization because the motor program can be executed more automatically by the individual without input, verbal, or cognitive processes. [37,130] When a new task is retained, it does not require the individual much attention to perform the task. Physical characteristics of the retention phase are hard to determine but would likely be observed through the proper motor performance of the new task without instruction or feedback and perhaps the ability to maintain the skill when a distraction is introduced.[128]

Table 1. *Markers and examples of motor learning by phase*

Phase	***Markers of Phase***	***Example Marker Relevant to Gait Retraining***
Acquisition	Accuracy with some error throughout the movement goal while receiving feedback	Accurately acquiring the target SR while auditory and/or verbal feedback is provided, potentially with occasional deviations in SR
Learning	Accuracy and consistency throughout the movement goal with less reliance on feedback	Accurately acquiring and maintaining the target SR with minimal or no exposure auditory and/or verbal feedback with less cognitive effort needed
Retention	Accuracy, consistency, and automaticity of the movement goal with no feedback and/or while distracted	Accurately acquiring and maintaining the target SR with no exposure auditory and/or verbal feedback in an automatic fashion, potentially while attention is focused on an outside task

Goal-action coupling: The OPTIMAL theory has connected goal-action coupling to optimal motor performance and learning. Goal-action coupling can be described as maintaining a focus on the goal of the new movement and preventing focusing elsewhere.[38] In the OPTIMAL theory model, goal-action coupling is produced by increasing the focus on the task goal (goal-focus) and decreasing self-focus. With more goal-focused practice, comes superior motor performance and, ultimately, superior motor learning. On the contrary, self-focus, or directing the attention within the self in response to instruction, can interfere with optimal motor control and learning.[128] Ultimately, as one is faced with the goal of accomplishing a new task, different networks of the brain would have to communicate and deactivate and activate accordingly.[128,138,139] The OPTIMAL theory guides clinicians in creating practice conditions that increase the functional connections between the areas of the brain focused on the goal (goal-focus) while deactivating the areas of brain focused within the learner (self-focus) as this is associated with higher motor skill levels.[141-143] Goal-action coupling is an important aspect of the OPTIMAL theory underlying mechanisms. Measurement of goal action coupling is primarily done by functional magnetic resonance imaging, which requires access to costly equipment and extensive training. However, the evidence demonstrates with the manipulation of autonomy, enhanced expectancies, and focus of attention clinicians and researchers can directly influence the neuroscientific adaptations to increased goal-action coupling.[38]

Practice Environment: Three elements identified as important to optimize motor learning are 1) enhanced expectancies, 2) autonomy, and 3) external focus of attention. When a researcher or clinician designs an intervention with enhanced expectancies, increased autonomy, and external focus of attention at the forefront, optimal motor learning practices are created. Enhanced expectancies and autonomy are both also found to influence intrinsic motivation.[38] Intrinsic motivation is defined as doing an activity for the inherent satisfaction (enjoyment or interest) the activity offers.[144] After each successful bout of motor performance and learning, intrinsic motivation is increased and enhanced expectancies for the next practice are achieved, which leads to further interest an enjoyment in the motor learning process. The cycle of optimal motor learning, also referred to as the virtuous cycle, is then furthered. Recent evidence has shown that enhanced expectancies, autonomy, and external focus of attention are additive in nature when optimizing motor performance.[44] That is, each of the elements independently contributes to improve motor learning but interventions are most effective when all three elements are included.[44] These elements will next be further explained and related to running gait retraining.

Enhanced expectancies: Expectancies are a range of forward-directed anticipatory or predictive cognitions or beliefs about what is about to occur.[145] Learner expectancies indicate how the individual perceives their ability to complete the task that is going to be performed, which can be positive or negative.[38] Enhanced expectancies in the context of the OPTIMAL theory refer to the positive expectations of upcoming performance on a task. These enhanced expectancies are typically informed by past performance accomplishments associated with the motor task or behavior.[38] *Circumstances that give the learner more positive expectations for the task at hand have been recognized as a positive predictor of better motor performance, retention, and transfer of skill.*[146]

The mechanisms in which enhanced expectancies improve motor learning and performance are physiological and psychological in nature. From a physiological standpoint, enhanced expectancies create a release of neurotransmitters dopamine and serotonin. Both dopamine and serotonin facilitate and strengthen memory and learning.[147,148] Serotonin has been found to make neurons more responsive to subsequent input, which "reinforces" the synaptic connection between sensory and motor neurons.[148] The communication between the sensory neurons that detect input throughout the new task and motor neurons that execute the new task are important particularly in the acquisition and learning phases of motor learning.[37] Dopaminergic effects produced by enhanced expectancies also are supported within the psychological evidence. Motor learning requires practice, as well. Dopamine has been identified as important to motivation.[149-151] perhaps because it is an essential part of creating the desire to continue "rewarding" behavior and maintaining the habit of the "rewarding" behavior.[148] In this case, "rewarding" behavior may be 1) performing a new motor task correctly, 2) receiving positive feedback on the new task, and/or 3) experiencing positive feelings while performing the task.[38] Enhanced expectancies also work to heighten attention to more task-relevant cues and suppress less relevant cues to the new task (goal-action coupling)[152,153] and build structural and functional connections in the brain that enhance skilled performance.[154,155] From a psychological standpoint, enhanced expectancies are likely working to increase feelings of confidence,[156] self-efficacy,[40] and positive affect,[41] which increase intrinsic motivation.[39]

Therefore, the OPTIMAL theory theorizes that steps be taken to ensure that the individual has overall enhanced expectations for the new task being required of them. Examples of constructs that may operationally define enhanced expectancies include but are not limited to 1) self-confidence,[39] 2) self-efficacy,[40] and 3) affect (emotions, mood).[41,42] For clinicians and researchers, there are several different ways to enhance expectations of a task for an individual. A few of the most prominent strategies that have been used in the literature include 1) using positive feedback, 2) altering perceived task difficulty, and 3) providing an experience that creates positive affect.[38]

Positive feedback: Highlighting the individual's best performance on the task through positive feedback will enhance expectancies.[38] For the purposes of this section, feedback will primarily be categorized as augmented feedback. Verbal feedback consists of information provided to the learner by some outside source, such as a clinician.[37] "Knowledge of results" is a typical condition in which augmented feedback is given to the learner regarding the degree (good/bad, accurate/inaccurate) to which they performed the task. Using knowledge of results provides the learner with information on how they are doing on accomplishing the task-goal.[157] Early research proposed the guidance hypothesis, which states that providing feedback related to poor performance assists in correction of errors by guiding the individual to the desired outcomes.[157] It has since been suggested that creating a practice environment where an individual is repeatedly made aware of their mistakes decreases the person's motivation to partake in practice and negatively influences their ability to learn.

In current research, most literature regarding motor learning feedback surrounds the effects of positive feedback, which highlights the learner's correct trials of the task.

All using consistent methods, studies have shown that increased self-confidence,[156] intrinsic motivation,[39] and self-efficacy[40] produced by positive feedback accompanied superior motor performance, learning, and retention.[39,40,156,159] Findings have been tested across tasks[39,42,156,159] and various populations[160] and yielded equally favorable results for the use of positive feedback. In one study, it was reported that participants that received negative feedback were not able to produce effective practice or effective subsequent learning of a new skill.[40] In runners specifically, positive feedback has also increased running efficiency, reduced perceptions of effort, and increased positive affect.[42] Studies have consistently shown that using feedback after successful trials (positive feedback) when compared to unsuccessful trials (negative feedback) results in more effective learning, likely through mechanisms of increased intrinsic motivation, self-efficacy, and improved performance.[39] [40,159-161] Besides the physical and psychological evidence in favor of positive feedback, it was also determined that learners indicated they wanted feedback after successful trials rather than unsuccessful trials.[162] Using positive feedback within gait retraining protocols may accompany many psychological and physiological benefits that, when combined, optimize the potential for motor learning to take place.

Perceived task difficulty: If an individual believes a task will be difficult for them to complete for one reason or another, they already have negative expectancies about how they will perform on the task.[38] As stated, a belief that the new task will be relatively easy for a learner to complete is imperative to motor performance and learning.[163,164] Damisch et al.[165] demonstrated that the superstition of putting with a lucky ball has influenced motor performance and learning. Evidence like that of the "lucky ball" study[165] show even the most delicate components of can change perceived task difficult and needs to be considered prior to design of motor learning interventions.

One study reported improved motor performance and learning through redefining "correct" performance of the task to be slightly easier or telling an individual they have performed better than their peers.[164] This study also discovered individual's self-efficacy was improved, as well.[164] Studies have created easier criteria within practice conditions and reported superior motor performance and retention when compared to those with harder criteria in practice conditions.[166,167] Easier criteria for tasks have also led to improvements in self-efficacy and competence and task interest and enjoyment.[166] Ultimately, giving learners easier task goals when performing a new task may result in more effective learning and retention of the new movement. Although possible, changing the difficulty of the task may be counterproductive when the new movement goal is specific, such as in gait retraining. When the task itself cannot be greatly altered, it would be beneficial to select tasks that are subtle and manageable changes to make, especially during the early phases of motor learning. Researchers and clinicians can also pay attention to perceived task difficulty by providing an intervention that mimics the typical way someone performs the task. For example, runners may have shoes they prefer to wear. If that is the case, forcing the runner to wear a different shoe may change their perceived task difficulty because they cannot wear their typical shoes. As shown, small details of the task may influence perceived task difficulty and should thus be considered when designing gait retraining interventions.

Positive Affect: Affective valence is defined as a valanced response that lies on a continuum from good or pleasant, to bad or unpleasant.[168,169] Facilitative affect, often but not exclusively referred to as positive affect, would fall towards the good or pleasantness on this scale, which can be influenced by positive emotions or positive mood states. [168,169] Affective valence may be most evident in moods and/or emotions, but there are sheer differences in affect, emotions, and moods.[170] Emotions are typically viewed as immediate responses to specific stimuli characterized by short durations and high intensities (happiness, sadness, fear, or anxiety).[168,169] Emotions are more specific than affect and moods. Moods have been described as responses to how we see the world in a particular point in time.[171] Moods are more diffuse, longer lasting affective states where there is no specific target or origin of the state (depression or enjoyment).[168,169] Positive affect has been shown to indicate intrinsic motivation[172] as intrinsic motivation is marked by task enjoyment (a positively valanced mood). There is also evidence to suggest that positive affect increases cognitive flexibility and creativity, which can facilitate motor learning.[173-175]

Positive mood inductions have been found to benefit persons with Parkinson's disease when performing cognitive tasks.[41] Ridderinkhof et al.[41] used a Charlie Chaplin slapstick film clip in attempt to increase positive affect prior to performance of a motor-cognitive task. Results of this study indicated that positive affect may influence motor-cognitive learning and facilitate the neurophysiological processes that assist with task completion. Stoate et al.[42] discovered that positive affect was increased in runners that received positive feedback about their running performance and efficiency. Ultimately, the results of this study reinforce that positive affect can be induced with something as simple as positive feedback regarding performance from another individual. Performing a task successfully, having basic psychological needs met, and/or external rewards are proposed mechanisms for increasing positive affect within the OPTIMAL theory.[38] However, there are many other ways to induce positive affect that can be done in conjunction with motor tasks that have yet to be explored, such as music.

Music and Enhanced Expectancies: Models of the effects of music on exercise indicate that music can have psychological, physical, and psychophysical effects that will enhance expectancies. These effects are based on personal factors,[56,57,64,65] situational factors,[56,57,66-69] the qualities of music,[70-74] and an individual's experiences surrounding the music.[71]

Psychological effects entail the impact music can create on mood, emotion, affect, cognition, and behavior.[71] Music activates the prefrontal cortex,[176] which is associated with enhanced affective states and motivation.[177] Exercisers report music as a source of motivation during their exercise.[55-57] Music is a very simple way to create optimal motor learning through improved intrinsic motivation. A recently conducted meta-analysis by Terry et al.[52] indicated that music is likely to enhance positive affect (g= .48). Other studies have shown that positive affect[48-51] can be produced by using music during exercise and this would be beneficial for motor learning. Still, few studies have proposed that music can be used to create enhanced expectations for motor learning.

Physical effects of music would describe the effects on physiological function. From a physiological perspective, music rhythm creates neurological responses that optimize motor control, sensory perception, and attention.[61] Through these neurological processes, there is improved muscle coordination,[61] increased endurance,[62] exercise performance,[69,178] and motor skill acquisition.[55] When an individual is more energy efficient, measures of physiological function may be indicative of less exertion, such as decreased HR. On the other hand, the individual may exert themselves to a greater degree when music is present due to the energy efficiency and physiological variables may appear higher for this reason. Either way, depending on the goal of the individual during the workout, it is likely that the physiological changes that occur when music is used during practice would result in enhanced expectations for the next bout of practice.

Psychophysical effects describe the psychological perceptions of one's physical state.[71] As psychophysical effects tell researchers and clinicians about how the individual perceives their experience, such as how fatigued or how much pain they are in, these are significant measures to consider if the goal is to enhance expectancies. A common way to measure psychophysical effects of perceived fatigue and discomfort is with the Borg 15-point RPE scale.[179] Subjective feelings of discomfort or fatigue can be alleviated when individuals use music during exercise.[42,54-57] Terry et al.[52] discovered that music does significantly reduce RPE.[179]

Many individuals prefer to listen to music when they exercise, especially runners.[46,180] It is important to acknowledge the role of music because foreknowledge of the removal of music is theorized to impact the typical ability to perform an exercise.[47] Thus, removing music from an activity that music is typically used for, may create diminished expectancies (increased perceived task difficulty and less positive affect) and negatively impact motor learning. As music can decrease the amount of exertion the individual is perceiving during practice, it can be explored as a potential way to enhance expectancies particularly during more aerobic, continuous activities like running.

Autonomy: Autonomy is having the ability to control one's actions, is a basic psychological need[43] and, quite possibly, a biological necessity.[181] Practice conditions that cater to autonomy of the individual have been shown to optimize motor performance and learning.[182,183] Learners that can control the practice conditions may exhibit increased self-efficacy when practicing the task and therefore feel more success regarding their performance.[38] Physiologically, it is thought that involving the learner more actively throughout the learning process promotes deeper processing of information relevant to the task.[184-186] When autonomous practice conditions are emphasized there is also evidence of promoted error processing.[63] It is also widely accepted that when autonomy is honored in the motor learning phases,[187] learners are more intrinsically motivated,[188,189] and interested in the task.[190] The OPTIMAL theory outlines methods primarily directed at manipulating feedback to cater to more autonomous practice environments.

<u>Frequency of feedback:</u> Autonomy can be given to the individual learning the new task when using self-controlled feedback. Self-controlled feedback consists of giving the learner the ability to ask for feedback when they choose to. In the context of this study, self-controlled feedback would consist of the researcher providing verbal feedback only when the participant asked for it. For example, the participant may ask "How am I doing?" when given a new running gait. Janelle et al.[191] reported that self-controlled feedback conditions led to less need for feedback. Results such as these lead to the idea that when self-controlled feedback is used, learners may not need as much input from the researcher to acquire, learn, and retain the new

skill. Researchers have also found that the use of self-controlled feedback improves motor learning outcomes across tasks.[162,191-194] It also appears that when self-controlled feedback is used, participants indicated they mostly desire feedback after good trials. which enhances motor performance. Most clinicians may gravitate towards providing researcher-controlled feedback after poor trials.[193] Therefore, more intentional uses of self-controlled, positive feedback should be implemented into gait retraining protocols by predominately using positive feedback on gait alterations when the participant solicits it.

Instructional language: Besides how often feedback is being given, the language used in feedback also requires attention. Two main ways to word feedback are autonomy-supportive or controlling. An example of autonomy-supportive language is: "You may want to select a speed you are comfortable with when running today, such as something you can maintain for approximately 30 minutes." An example of controlling language is: "I want you to select a running speed that you can maintain for 30 minutes of running." Instructions that give the participant a sense of choice have been shown to lead to superior motor learning, such as better accuracy, in practice and at a retention test over controlling language.[195] To create a more autonomy-supportive script for verbal feedback, it would be beneficial to phrase the instructions as suggestions for the person rather than demands. Typically, autonomy-supportive language is not utilized often in gait retraining studies since research studies are largely controlling for variation within participants. However, the lack of autonomy-supportive instruction can certainly impact motor performance. My study will design the research script based on the example script provided by Hooyman et al.[195]

Incidental choices*:* Interestingly, research has reported that even the slightest bit of choice can create change in motor learning outcomes. Lewthwaite et al.[190] demonstrated that the ability to select golf ball color, a decision not related to the motor skill of golf putting, created learning differences when compared to those that were not allowed to select the ball color. This study posited that the respect of learner opinion is a small, yet effective way to support autonomy and thus improve motor learning. Typically, motor learning performance is not quantified by kinetic variables. However, Halperin et al.[196] set out to examine punch force and velocity under more autonomous conditions. Elite kickboxers were allowed to select the order in which they performed three types of punches. The methods used in this study are often referred to as self-controlled practice conditions. Those that had a choice in the order yielded higher impact force and velocity in their punches than those who were told the order in which to perform the punches.[196] Although gait retraining research aims to control variation for generalizability of results, providing incidental choices can impact motor performance and motor learning without disturbing the integrity of the study. For example, if using an auditory cue, providing options of cueing that the participants can choose from provides autonomy without changing the movement goal drastically.

Using music to increase autonomy: From a clinical standpoint, there are several ways to create a more autonomous environment for patients. When there is autonomy support, there will likely be increased motor performance and facilitated motor learning and retention.[38] In general, autonomy and choice are rarely considered within gait retraining protocols. Therefore, research exploring new methods to accomplish the gait retraining task goals is needed. Incidental choices are unlikely to alter the task goal but have increased motor performance and learning.[190,196]

Music selection during gait retraining is an easily implemented incidental choice to introduce. As stated, musical effects on exercise are based on personal factors,[56,57,64,65] situational factors,[56,57,66-69] the qualities of music,[70-74] and an individual's experiences surrounding the music.[71] For this reason, it is suggested that self-selected music be used in research to ensure the motivational qualities of the music are specific to that individual.[56,57] Fortunately, this provides researchers and clinicians a great opportunity to optimize motor learning by increasing autonomy within the practice environment. The use of self-selected music has not yet been shown to influence motor learning so future research should explore this relationship.

External Focus of Attention: Attention has several definitions depending on scientific discipline. Attention may refer to 1) task and environment monitoring, 2) monitoring scope or breadth of physical and other cues relevant to task performance, 3) the skill or ability to control concentration despite conflicting inputs or distractions, or 4) concentration on content regarding particular movement-relevant cues.[38] Attentional focus is considered the information at which the performer's attention, or consciousness, is directed.[37] One dimension of attentional focus is the direction of focus. Directions of attentional focus include external focus or attending to the consequence of the action to be produced, and internal focus, or attending to the movements of the body that make the action.[37] When external focus cues are used, it is said to increase automaticity[38] and unconscious, fast, and reflexive control processes.[197,198] To restate, automaticity is when there is less cognitive activity needed to perform the motor task.[37] The effect of greater automaticity is better movement fluidity,[199] increased use of reflexive movement adjustments,[200] and more effective dual-task performance.[199] The mechanism speculated to lead to greater automaticity through external focus cues is due to the prevention of internal attentional distractions when the attention is directed externally.[197,199] According to the constrained action hypothesis, internal focus induces a conscious type of control, which constrains the motor system by interfering with the automatic control processes of the brain.[133,197] Finally, it is theorized that learners who concentrate on external focus cues use faster feedback loops than those who concentrated on internal focus cues.[197,200] Indirectly, it should also be noted that successful performance that accompanies external focus cues then foster enhanced expectancies.[38] According to the OPTIMAL Theory, external focus cues are associated with achieving higher skill levels more quickly,[201] which has been demonstrated on a variety of tasks with various task goals.[38]

Movement effectiveness: Movement effectiveness is one common task goal that has been assessed to determine the effects of external focus cues. Examples of movement effectiveness would include accuracy, force production, and maintaining balance.[38] Research has shown that balance is improved when the learner's attention is directed externally.[200,202-205] For example, directing learner's focus to movement of a balance platform was found to be more effective than directing learner's focus to the movement of their feet in a number of studies.[200,202-205] Ducharme et al.[206] also found that external focus produced more effective responses to perturbations. Accuracy is another improvement in motor performance observed when learners' attention is directed externally.[207,208] When participants were asked to produce the desired amount of force or aim at a target, they were most accurate during practice, retention, and transfer tests while focusing on an external focus.[209-214] Movement effectiveness is certainly relevant to some tasks, but may be more applicable to tasks that have a clear end goal, such as a target to aim at.

Movement efficiency: When a movement pattern is executed with less energy expenditure it is considered efficient.[38] Examples of movement efficiency include decreased oxygen consumption, decreased heart rate, maximum force production, increased movement speed, or increased endurance.[38] To produce maximum forces, the muscles must channel optimal coordination. External focus cues have insighted greater maximum force production in comparison to internal cues on isokinetic tasks[215] and more sport-related tasks.[201,216-220] With greater maximum force production, studies also discovered less muscular activity, as well.[215] Findings such as this cater to the argument that the muscles are better able to coordinate and produce optimal outcomes while still remaining efficient. Speed and endurance are essential to many physical tasks. External focus also has yielded greater movement speed[217] and endurance.[221] Reduced heart rate and electromyographic (EMG) activity was noted for sit-up performance when external focus instruction was given, but range of motion was actually increased, indicating the sit-up form did not suffer despite the decreased EMG activity.[222] In fact, many studies have discovered movement form improves when an external focus cue is used. Both expert movement analysis[223] and kinematic assessments[224,225] have been improved when external focus is utilized over internal focus.

Limitations of the OPTIMAL Theory: There has been some debate about an exclusive gravitation towards external focus instruction. Maurer and Munzert[226] indicate that familiarity of the task instructions, or familiar instructions, can increase automaticity of the task. Internal focus was also found to be preferred by many of the basketball players included in this study. Some researchers argue that attentional strategies may become a main source of information for that individual to perform the whole skill.[227] For this reason, asking someone to change their preference or already established source of how to complete the task may be counterproductive. Additionally, when an individual does perform a skill with automaticity, directing attention to any other focus may be disruptive to them. In theory, external focus of attention decreases disruptive self-focused processing. However, there is an argument that some of this cognitive processing is fine if it does not overpower attentional processes.[228] While this may be true, it remains supported that external focus cues are likely more effective for those learning a new skill.[38] Perhaps the best strategy to begin to implement responsible instruction would be to aim instruction at the movement outcome (externally) but provide further details in terms that the learner can understand, if needed.

The OPTIMAL theory comments on motivation and attention, on motor performance and motor learning outcomes. Within a rehabilitation setting, there are many other variables that can influence overall rehabilitation outcomes, though. Models, such as the Biopsychosocial Model of Sport Injury Rehabilitation developed by Brewer et al.[229] describe variables that may interact to influence rehabilitation outcomes including injury characteristics, sociodemographic, biological, psychological and social/contextual factors. A commonly manipulated variable within the Biopsychosocial Model of Sport Injury Rehabilitation is the rehabilitation environment. Changes within the rehabilitation environment directly influence biological and psychological factors, which then influence rehabilitation outcomes. The OPTIMAL theory doesn't account for injury characteristics, or all sociodemographic, biological, psychological, and social/contextual factors, but is instead more focused on the adaptations that can be made to the rehabilitation environment to optimize motor learning interventions. For the purpose of this study, the manipulation of the rehabilitation environment was the focus, which is why the OPTIMAL theory was selected. However, the variables that have not been accounted for are recognized as limitations.

Summary of the OPTIMAL Theory and gaps in the literature: Motor learning is a complex process with both cognitive and motor processes occurring throughout, simultaneously.[37,131,132,230,231] To summarize the literature on motor learning we can start by acknowledging there are many ways to assess motor learning. It is said that motor learning cannot be directly observed entirely,[37,128] so many researchers and clinicians observe movement to confirm learning has occurred.[128] The analysis of movement or movement change is a common clinical practice for prevention and rehabilitation of sport-related injury. Therefore, it is imperative that movement analysists understand motor learning mechanisms and best practices to optimize motor learning.

The OPTIMAL theory proposes actions that can be taken to assist in the process of motor learning by accessing neuroscience and sport psychology evidence.[38] Through the use of the OPTIMAL theory, clinicians and researchers can produce dopaminergic effects to aid in motor learning processes.[147-151] Intrinsic motivation is also found to be an important mechanism to motor learning.[38] However, few studies within the sport injury rehabilitation discipline have tapped into these biological and psychological constructs to benefit the motor learning process. Currently, studies aimed to retrain movement have only explicitly stated traditional motor learning theory principles that have framed their intervention development when other models. Several strategies to enhance dopaminergic effects and intrinsic motivation are discussed in the OPTIMAL theory.

Enhanced expectancies can be accomplished by using positive feedback,[39,40,42,156,159,160] altering perceived task difficulty,[163-167] or inducing positive affect throughout the practice.[41,42] Positive affect is included as a method to improve expectancies[41] but has not been as widely explored. Comedic videos[41] and positive feedback[42] have created positive affect and better motor learning outcomes. Music is a common preference for runners and exercisers that accompanies positive affective states and decreased perceptions of exertion.[42,52,54-57,179] However, the effects of music on biomechanics and motor learning have never been explored.

Increased autonomy may be accomplished by allowing for choice within the practice setting. Providing autonomy is beneficial to motor learning and is commonly accomplished by using autonomous instructional language,[195] providing choice on details not related to the movement task,[190,196] and allowing self-controlled feedback.[162,191-194] In research settings, where confounding elements must be controlled, it is understandably difficult to allow for autonomy. Autonomous instructional language is promising to include in motor learning interventions, as it is relatively easy to control and apply to each participant. Choices not related to the task are also a reasonable way to create a more autonomous laboratory space. When the task goal of the new skill is to decrease injury, there is likely little space for alterations of the intervention. Typically, methods that have worked to decrease injury are often the methods that researchers continue to use to cue these changes, which doesn't allow for much of an autonomous experience. Investigation of supplemental methods that yield similar task outcomes will allow clinicians to provide more options in the clinical field. Using self-selected music can create autonomy in the motor learning environment but introducing music has not yet been explored.

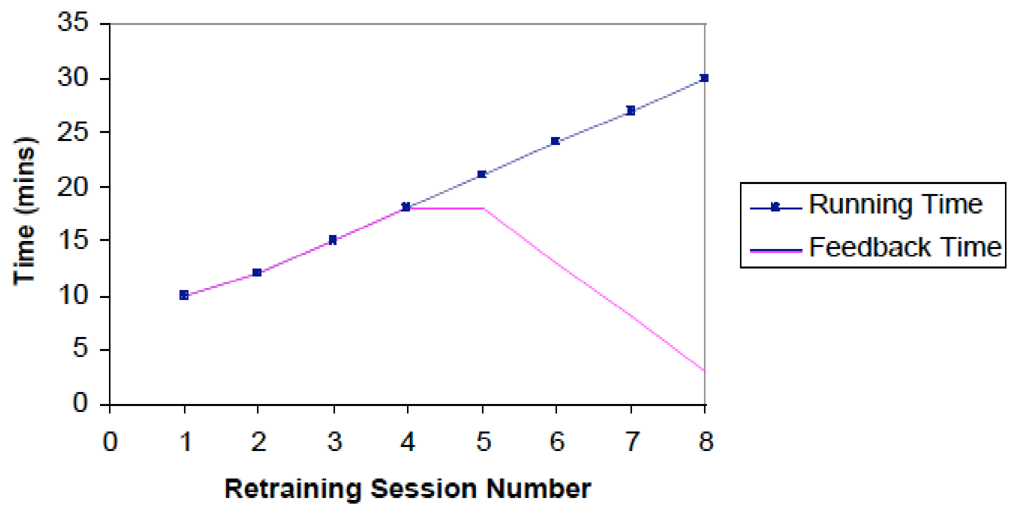
Using an external focus of attention is accomplished when the feedback is directed to the movement effect rather than within the body.[37] External attentional focus has received much attention from researchers as it is shown to increase automaticity[197,199,200] needed for retention of learning. Some learners may already have a familiar form of focus they choose, or they may already have an automatic movement pattern.[226] Thus, bringing attention to unfamiliar cues or calling for attentional focus at all may be counterproductive.[226,228] Still, it appears that there is sound evidence that, from a physiological standpoint, external focus of attention may provide optimal outcomes for motor learning.[200,202,204-208,211,215-219,221,232] Researchers using this feedback may have to be prepared to clarify external cues based on the individual, but should employ external focus cueing when possible.

Gait Retraining:

Studies have primarily used three different gait retraining strategies to decrease harmful running biomechanics using kinematic gait retraining,[15,17,18,22-24,92-95,97,109,110] kinetic gait retraining,[233-235] and temporospatial gait retraining.[30-34,36,81,236,237] Common movement goals of kinematic gait retraining include but are not limited to reducing hip adduction[86,88] and altering foot strike angles.[87,238] Theoretically, reducing hip adduction[110,239] and forefoot striking may produce decreased PFJ loading throughout running.[87,240] Kinematic gait retraining is effective to decrease magnitude of loading and has been accomplished with the use of real-time visual cues of running impact and verbal cueing to "land softly" while running.[233-235] Temporospatial gait retraining calls for the movement goals of shortening stride length[241,242] or increase of running SR. Manipulation of temporospatial characteristics of gait are speculated to decrease impact loading by moving the impact magnitude toward the midfoot,[243] decreasing overall loading at the knee,[31,32] and increasing leg stiffness and shock attenuation.[244] Changes to kinematics,[245] such as foot strike pattern,[246,247] or kinetics, such as mitigating impact, have also been shown to adjust temporospatial variables of gait. Since lower SR has also been directly related to increased risk for RRI,[35] increasing SR has been the direct focus of gait retraining interventions, as well. There are many types of gait retraining that call for different movement goals. The "best" options may be dictated by examining the literature closely.

Method Designs of Gait Retraining Studies: Generally speaking, current gait retraining studies have considered motor learning principles when designing intervention schedules. Gait retraining methods have typically applied the guidance hypothesis of motor learning to aid in producing better outcomes. Guidance hypothesis states that some form of feedback is needed in order to instruct the learner what they need to change and that this feedback must not be applied so frequently that it is relied on.[248] Several forms of feedback have been used in gait retraining protocols including but not limited to verbal feedback,[30,36,81,86-88,233-236,238,249] visual feedback,[86-88,233-235] and auditory feedback.[31-34,36,81,236-238,249] Faded-feedback designs entail gradually removing feedback over the course of practices, which has been shown to produce superior motor learning results.[250-252] In a recent review, Davis et al.[28] noted that outcomes of gait retraining studies were improved to a greater degree when a faded-feedback design was used in runners with PFP. Crowell and Davis[234] were the first to propose the 8-session, 2-week, gradually decreased feedback schedule that most studies have used. It is hypothesized that since the principles of motor learning were included in the design of this study, retention of new motor patterns were found. Since this study, several gait retraining studies have adopted this faded-feedback schedule (Figure 4).[86-88,233,234,238,249] In general, runners undergoing a gait retraining would begin the first session running for a shorter period of time with continuous feedback. Each time the runner returns for another session of gait retraining, the time they practice is increased, the time they receive feedback is decreased, or both.

Figure 4. *Faded feedback gait retraining schedule commonly employed in the literature.*



Limitations and knowledge gaps of methods of gait retraining: According to some evidence, the use of a faded-feedback design is warranted.[252] However, it is unclear if there is a threshold for the number of sessions or time spent running before motor learning begins. SR gait alterations have been demonstrated by runners within as little as 5 minutes and when feedback was removed runners were able to maintain the new gait modifications. [32,81,235] These findings may suggest that the acquisition phase, often accompanied by the need for frequent feedback,[37] may be occurring within very small time frames while learning, often marked by the need for less feedback,[37] may be occurring within the first session of gait retraining. Recent preliminary data indicates 15 minutes into the first session of gait retraining, participants have consistently altered gait.[253] Small incremental changes were noted in gait alterations after only 4 sessions of gait retraining,[253] which is an indication of moving into the learning phase.[130] After the first session, gait alterations were made nearly instantly,[253] which can begin to signify retention of the movement pattern.[37,128] One major limitation of gait retraining protocols often discussed is the large time commitment. Shorter term schedules that produce positive results would be more universal for clinical integration.

Besides the time commitment that current gait retraining protocols use, there are some studies that have used rather inaccessible technology for feedback methods. Many studies using

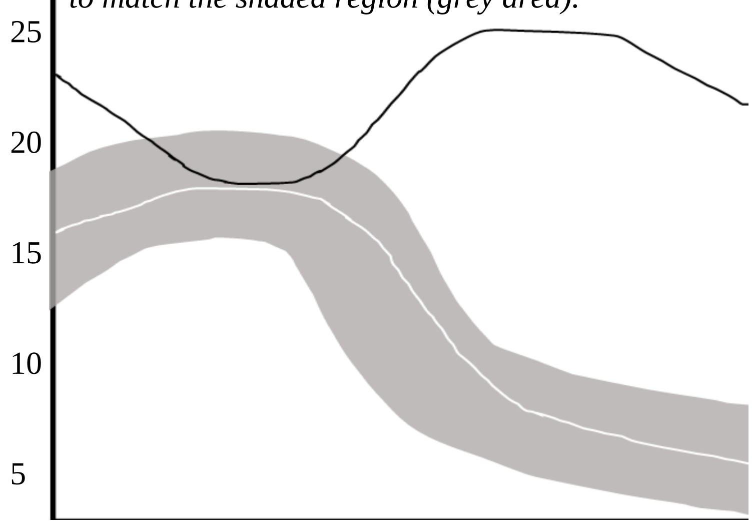


Figure 5. *Screen image used during a real-time feedback gait retraining session. This participant would be instructed to lower their curve (black line) to match the shaded region (grey area).*

real-time feedback have relied on three dimensional (3D) kinematic or force plate systems to monitor and provide feedback.[86] Figure 5 is an example of how real-time visual feedback is presented. Specifically, a biomechanical variable is selected as the movement goal, such as hip adduction. While the individual runs, a real-time graphical curve representation of the amount of hip adduction during their running is projected on a monitor (black line in Figure 5). Also included on the graph is a shaded area that would represent the target area for the runner to aim to align their curve with (grey area and white line in Figure 5). As most of the visual feedback methods used to retrain gait[86,233-235] would not translate to clinical practice, it is imperative to also explore gait retraining techniques that are versatile enough to be used on the treadmill or outdoors and require minimal equipment. The use of auditory feedback has been found to be a more effective strategy for motor learning when compared to visual feedback.[254] Therefore, efforts must be placed towards generating translatable gait retraining methods that are accessible to clinicians working outside of the research lab. Potentially, better motor learning outcomes would be produced using auditory feedback.

Kinematic Gait Retraining: Increased hip adduction during running would present as collapsed knees or less space between the knees during running[104] which has been shown to alter the distribution of loading within the LE[17,109,110] and increasing risk of RRI. Noehren et al.[86] provided some of the earliest evidence that gait retraining to alter hip kinematics can improve patient rated outcome measures and hip biomechanics. Using the gait retraining schedule[234] and visual, real-time feedback methods described above, peak hip adduction, contralateral pelvic drop, and pain levels were reduced immediately following the retraining and 1-month after the intervention. Similar results were found when using a mirror to provide visual feedback.[88] When using the mirror technique, hip adduction did begin to increase slightly towards baseline levels at

1- and 3-month post-intervention though, suggesting lack of retention. However, both in-lab and accessible methods have been employed and resulted in primarily retained changes to hip kinematics.

About 90% of recreational runners adopt a rearfoot strike (RFS) pattern.[255] A RFS means the individual's heel contacts the ground at initial contact. A RFS pattern has accompanied a distinct impact peak in vGRF in the early stance phase of running.[243,256] Researchers have thus begun to investigate if changing the foot strike pattern of individuals may lead to decreases in loading. Alternatives to RFS include midfoot or forefoot strike (MFS or FFS, respectively). MFS means the individual contacts the ground with the midsole of their foot at initial contact and FFS means the forefoot contacts the ground at initial contact. Typically, RFSers display higher degrees of ankle dorsiflexion, MFSers display more neutral ankle angles, and FFSers display more plantarflexed ankle angles at initial contact.[257] Since the goal of retraining foot strike pattern is often to increase the amount of plantarflexion at the ankle (RFS to FFS) during running, it can be considered a kinematic alteration. Roper et al.[87] used the same retraining schedule[86,88,234] and a mirror[88] to alter foot strike pattern in runners with PFP. Those in the FFS gait retraining group had increased knee flexion, reduced knee abduction, more plantarflexion of the ankle at initial contact, and improved reported pain when compared to the control group after the intervention. All kinematic changes except increased knee flexion remained at the 1-month posttest. This study also determined that PFJ contact force and stress was decreased in those who retrained to adopt a FFS. There are shown benefits to adopting a FFS and this gait pattern can be retained in runners with PFP.

Limitations of kinematic gait retraining: Perhaps partially due to the relationship between kinematics and PFJ contact force[17,87,110] much of the research on kinematic gait retraining has been completed on runners with PFP. The decreases in pain and increases in function reported in these studies[86-88] have led to gait retraining being a suggested treatment for runners with PFP.[258,259] Still, there are several limitations to specifically targeting kinematics when selecting a gait retraining protocol.

Most studies have found that retention of certain kinematic changes can be accomplished from up to 1 and 3-months after retraining,[86-88] but some kinematic adjustments may drift back to baseline levels.[88] One limitation to the kinematic gait retraining literature is that each study aimed at kinematic movement goals were conducted in lab settings. To change kinematics, 2-weeks of practice in a lab setting may be sufficient to reach the learning stage, but retention past three months may require more practice in a non-researcher-controlled environment. For example, outdoor running involves changes in terrain and adjustments to speed that may have to periodically take place. Recent evidence suggests that running kinematics are more sensitive to terrain and speed changes associated with outdoor running when compared to SR.[260] It is possible that practice and retention of kinematic movement goals may be interrupted when running outside of the lab environment, which is a common preference for runners.[6]

Kinematic movement goals may also be more complex for the learner to understand. Primarily when altering hip adduction, researchers provided the individuals with verbal cueing on *how* to make the changes in kinematics along with visual cueing.[86,88] Perhaps verbal cues used in these studies are difficult for runners to discern or controlling in nature. Willy et al.[88] indicated that throughout pilot testing, runners often widened their stance or pointed their toes outward in order to follow the verbal instruction to gain “better” alignment. These two strategies were noted as a maladaptation on the runner’s part versus an indication that the selected researcher script was not clear or easily interpreted by the runner. It is important to remember that clear verbal cues that are easily understood or familiar instruction may aid in the cognitive processes[37] being relied on in early stages of motor learning.[226,227] In addition, controlling instructional language can interfere with the learner's autonomy and disrupt motor learning processes, perhaps accompanying more time spent in the early stages of motor learning or lack of retention of the new gait pattern.

Conversely, studies altering foot strike kinematics did not report similar confusion surrounding the verbal cues used in the gait retraining protocol.[87,238] The literature supports that transitioning to FFS pattern may be best practice for those runners with the specific diagnosis of PFP.[28] However, adopting a FFS may not be the most suitable option for healthy runners or those with lower leg or foot RRI. FFSing may reduce PFJ loading,[87,240] but it also increases Achilles tendon and forefoot loading, which may accompany new injury and/or exacerbate other previous injuries.[83,240] Notably, a quick progression to a FFS pattern without a strengthening protocol first may increase the risk of bone stress injury to the foot[261] and clinicians may not have the time for the lengthy process required to transition safely. Still, due to the decreased impacts that are observed with a FFS,[91] some speculate that FFS running patterns should be the goal for all runners. Recent evidence suggests that changing foot strike pattern within uninjured runners cannot currently be suggested because most of the evidence linking injury to RFS is retrospective.[262,263] Therefore, other methods to decrease loading have been explored.

Kinetic Gait Retraining: Kinetic gait retraining is the only gait retraining to currently have prospective evidence[233] indicating it is an effective prevention technique. Chan et al.[233] conducted a study in which 320 novice runners completed a 2-week[86,88,234] gait retraining program. In addition to the real-time feedback method described above, runners were told to "run softer". After this gait retraining intervention, lower VLR across running speeds were found. The researchers then followed all novice runners for one year to determine if gait retraining decreased the incidence of RRI. It was discovered that the retrained group experienced a 62% reduction in RRI compared to those who did not receive retraining. The reduced RRI could be due to the retraining the runners received, however, there was no long-term biomechanical assessment that confirmed the runners in the retraining group retained the changes to their running gait beyond the 2-week posttest. Still, these prospective results provide strong rationale for gait retraining protocols that reduce VLR to be utilized for healthy runners.

Crowell and Davis[234] aimed to decreased tibial acceleration and VLR using real-time feedback methods and cues to "run softer" and "make their footfalls quieter". Decreases in tibial peak positive acceleration and VLR immediately after the protocol and these changes were retained one month later after each runner was told to use their new running gait for the next four weeks. Although there was not specific monitoring to confirm the individuals complied to the new gait pattern, 1-month follow up results suggest motor learning and retention. Since reaching the learning and retention phases cannot be accomplished without practice,[37] it is possible prescribing participants to use their new gait pattern is an effective way to induce practice.

Creaby et al.[235] used 10-minute retraining sessions. Some runners were told to "run softer" and "make your footfalls quieter" while receiving positive and negative, researcher-controlled verbal feedback. Some runners were allocated to a real-time visual feedback group. After 10 minutes, participants were told to continue their new gait pattern for the next 10 minutes. All runners were able to decrease their tibial peak positive acceleration directly after and one week later while receiving no feedback. Interestingly, only 10 minutes of gait retraining resulted in retention of the new gait pattern at least in the short term. Findings such as these support the need to examine gait retraining dosage.

Limitations of kinetic gait retraining: Loading is a widely recognized variable that could increase risk of RRI. [18-22,91,92,97] Therefore, studies have been focused on decreasing impact and loading variables with various forms of gait retraining protocols. Overall, there is sound theoretical evidence to support that kinetic gait retraining can be effective to prevent injury.[14,233] However, several limitations exist in the current body of literature on kinetic gait retraining.

All the studies that aimed to alter kinetics during running used a vGRF or acceleration curve generated in real-time as visual feedback.[233-235] As stated, this form of real-time feedback is not likely to be clinically accessible and cannot be utilized outside of a research lab. One study using this method did indicate decreased loading was retained, but evidence is currently limited to the results of this one study.[234] Due to the selected lab equipment for these studies, the runner would be unable to use the same methods when returning to their normal running routine, which may impact retention. For this reason, the utility of these gait retraining interventions can be questioned. Additionally, the use of auditory feedback has been found to produce superior results over visual feedback when it comes to motor learning.[254] Other gait retraining methods using auditory feedback available to the runner in their normal environment should be explored.

Verbal cues to "run softer" were also used in these study designs. While more universally available, impact sound has recently been discovered to not be related to vGRF variables, specifically VLR.[264] Instead, it was determined that impact sound was a better indication of foot strike patterns. While studies have used verbal cues to "run softer" and found decreased loading, it is possible that foot strike is actually changing because of this cue. Findings such as these suggest that cues to "run softer" should not be relied on if the goal is to solely decrease loading variables without influencing foot strike patterns. As stated, changing foot strike patterns may be effective to reduce loading[238] and best for some patients, but contraindicated for others.[83]

The results of Creaby et al.[235] indicate that internal focus (used in the verbal cueing group) and external focus (used in the real-time visual feedback group) are possibly effective in the early stages of motor learning. However, the verbal feedback used in this study was not catering to enhanced expectancies as they selected to use negative feedback. There was also a lack of autonomy provided to the runners because the researcher-controlled feedback frequency. The highest percent change in tibial acceleration out of both groups and all follow-up testing points was a 28.1% decrease. Since each element of the OPTIMAL theory has been found to be additive to motor learning outcomes,[44] the effect of both interventions on tibial acceleration may have reached higher percentages of change if OPTIMAL theory principles guided the intervention design. Study designs should begin to consider how to better incorporate OPTIMAL theory to produce decreased loading rates.

Temporospatial Gait Retraining: Temporospatial gait retraining is a manipulation of stride length, step width, or SR. SR is, by far, the most commonly addressed temporospatial gait parameter within the literature.[30-34,36,237,238,249,265,266] The underlying purpose of this form of gait retraining is commonly to influence kinematics and kinetics. Typical strategies to increase SR are verbal cues entailing taking shorter/faster steps, match footfalls to auditory cues of a metronome,[31-34,36,237,249,265] a combination of both of these,[81,236,238,267] and/or through the use of a SR monitoring device.[30,36,81,266,268] It is currently recommended to only increase SR by only 5-10% is recommended to prevent excessive fatigue and ensure changes are manageable for the runner.[32]

Studies increasing SR in healthy runners all using similar method designs have demonstrated positive changes in injurious running biomechanics.[31-33,237] The methods were executed over a short duration, but likely provide insight on what biomechanical changes can be expected when reaching acquisition phase of an increased SR. Runners instructed to increase their preferred SR by 5%[32,33,237] and 10%[31-33,237] while being cued to match their footfalls to the beat of a standard metronome set to the target SR displayed, as expected, decreased step length and vertical excursion of the center of mass.[32] Kinetic changes, specifically peak vGRF and mechanical loading of the knee have been found when SR is increased by 5%[32,237] and 10%.[31,237] Patellar tendon force has been reduced by ~11% along with reductions in peak PFJ force can be acquired when increasing SR 10%.[31] Muscular activity during the pre and late swing phases of gait are also altered at a +5 and +10% SR conditions within the runners.[31,33] The changes in muscular activity are thought to provide insight into changes in kinematics that were previously found when SR is increased. Kinematic changes such as decreased peak knee flexion, [31,32] peak hip adduction, [32] peak hip internal rotation,[32] peak dorsiflexion,[237] and peak eversion,[237] have been found when SR is increased by as little as 5% above preferred SR. Peak tibial internal rotation can be decreased when running at a +10% SR.

Some biomechanical changes that have been seen at a SR increased by 10% were not also found at 5% increases However, RPE was found to be greater in one study using the Borg 15-point scale, when adopting a +10% SR. As discussed in the previous section, increased RPE may be a potential drawback to motor learning. Since increased perceived exertion on the Borg 15-point scale has been found to be a valid reflection of physical exertion,[269] negative connotations, such as feeling more exerted, may be produced when increasing SR 10% or greater. When motor learning, it is beneficial to enhance expectancies. As discussed above, improving psychophysical variables, such as RPE, is a common way to accomplish enhanced expectancies. Future research should consider the findings of this study when gait retraining to increase SR. Perhaps increasing SR 10% provides superior biomechanical benefits to the runner but may induce perceptions of greater exertion (a potential negative expectancy) that is not reported in the +5% running condition. If this inference is true, the benefits of a +10% SR condition may not be superior when motor learning is the goal of the intervention.

Due to the potential biomechanical benefits of acquisition of an increased SR the previous studies have demonstrated, researchers have begun to investigate the biomechanical benefits and motor learning of increased SR on those with diagnosed RRI. A feasibility study using more a long-term gait retraining protocol to increase SR in runners with PFP indicate an runners can, in fact, learn an increased SR.[34] Similar to studies testing acquisition, peak hip adduction, hip internal rotation, and knee flexion were all reduced after 18 sessions of retraining over the course of 6 weeks. Improvements in average and worst reported pain were also noted at the conclusion of the intervention. Corroborating the results of Chumanov et al.,[33] vastus medialis oblique peak muscle activity were altered at the conclusion on the intervention, as well. Strengths of this study include the use of a hybrid protocol in which one session of gait retraining a week for 6 weeks was completed with a researcher and the latter two sessions were conducted by the runner themselves. A protocol like this would be much more generalizable to standard clinical procedures. *When combined with previous research,*[31-33,237] *the literature supports that increasing SR can be acquired and learned in both healthy and injured runners with several biomechanical and patient-centered benefits.*

Comparative gait retraining studies including increasing SR: Studies have compared other common interventions used in RRI rehabilitation to gait retraining and found that gait retraining is, overall, an effective strategy.[236,270] Several studies have also compared various forms of gait retraining due to positive results found in hopes to uncover which may be "best". In a recent review, Barton et al.[83] discusses the many faults that come with deeming one gait retraining strategy generally superior to another, as each has their place. Although some studies have indicated favorable outcomes when using kinematic[238,249] gait retraining methods, SR retraining has been found to be superior to other methods of intervention.[236,270] in a clinical setting.

Bonacci et al.[236] compared the effectiveness of a gait retraining protocol increasing SR 10% when compared to the use of foot orthoses in runners with PFP. A faded-feedback schedule was used in this study and participants were instructed to use the metronome app during weeks 1-5 if they ran outside of the gait retraining sessions. The foot orthoses group attended four fitting sessions to ensure proper fit and were instructed to wear foot orthoses in their athletic footwear. Patient-rated outcome measures in the gait retraining group reported improvements were greater than the foot orthoses group. A global rating of change scale was used to determine perceptions of global improvement. Within the gait retraining group, there was a success rate of 86% but only 29% within the foot orthosis group. The use of foot orthoses is typical, and within this study, is a relatively easy and low maintenance intervention. Meaningfully, the scheduled gait retraining protocol resulted in very similar feasibility even with a more demanding schedule for the participants. *It is for this reason that gait retraining SR is likely to be translated to clinical practice and feasible for researchers.*

Esculier et al.[270] compared the effectiveness of three 8-week rehabilitation programs for those with PFP. Participants were allocated to either an education-focused group, which was given symptom management and training modifications, an exercise-focused group, which completed traditional strengthening exercises and received the same education as the previous group, or a gait-retraining group that underwent gait retraining in addition to the patient education. Improvements in patient-rated outcome measures in all three groups were noted and similar to one another. However, only the gait retraining group increased their SR and demonstrated decreased VLR during running. The addition of patient education did not interfere with movement goals. It has been found effective to educate patients on the purpose of motor re-learning,[228] so patient education would be an evidence-based edition to gait retraining protocols.

dos Santos et al.[249] compared three gait retraining techniques in runners with PFP. A gait retraining schedule similar to previously performed studies was used.[86-88,234] One group was instructed to "strike with the forefoot", one group was instructed to increase their SR by 10% using a metronome as an auditory cue, and the last group was instructed to "run with an increased flexed trunk posture". All groups experienced clinical benefits from gait retraining including improved self-reported pain and function at the 6-month follow up. As expected, the foot strike group adopted more ankle plantarflexion, the trunk lean group adopted more trunk flexion, and the SR group had a greater number of spm. However, no other expected kinematic changes were found. The mechanisms for clinical measure improvement in this study were not necessarily accompanied by biomechanical changes, as expected. The psychosocial aspects, such as social support provided by the researcher, that accompany receiving a treatment aimed to combat pain during running for those with PFP should not be overlooked by researchers. Although this study provided conflicting results of biomechanical changes underpinning clinical improvements, the intervention of gait retraining in general can still be considered effective because of the positive changes in self-reported pain and function that were found and maintained 6-months after the protocol.

Futrell et al.[238] recently conducted a study to compare the effects of foot strike modification to increasing running SR in runners with no diagnosis of RRI. During this assessment a modified Stroop distraction test[271] was also conducted while the participants ran. Participants were given a strengthening program for the lower leg muscles and feet. After approximately a month of the strengthening program, participants received their gait retraining using a previously established schedule.[86,88,234,249] The SR group was instructed to increase their SR by 7.5% and match their foot strikes to the beat of a metronome The foot strike group was instructed to change to a FFS pattern via verbal cues such as landing gently on the balls of the feet. Several other verbal cues on how the runner may acquire this change including “shorten stride length, land with feet under the hip, take faster steps, and try not to bounce” were given. Those in the foot strike group heard an audible beep when peak tibial acceleration was indicative of a RFS. Participants in both groups were asked to continue to use the new gait pattern after completing the gait retraining. SR increased within the SR group by 7.2% and within the foot strike group by 6.1%, ankle dorsiflexion decreased in the foot strike group, and VLR was reduced in the foot strike were observed and retained. Interestingly, and in contrast to several other studies, VLR was not statistically lower in the SR group at any time points, although the SR of the group was significantly higher. Within the study, the foot strike group was given minimalist shoes while the cadence group was given conventional neutral shoes. It has been shown that minimal shoes may induce movement compensations to help mitigate loading during running.[272] The same compensations may not be employed when individuals are in conventional shoes. In fact, a more cushioned shoe has been found to increase impact forces during running.[273] Perhaps the difference in shoe wear used in this study do not truly allow for comparisons to be made between these two gait retraining techniques.

Limitations and knowledge gaps of temporospatial gait retraining: Temporospatial gait retraining has produced promising changes to potentially injurious running biomechanics such as decreasing loading,[30,36] hip adduction,[31,32] knee flexion,[31,32,34] PFJ loading,[31,274] ankle eversion,[237] and increasing activity in protective muscle contractions.[33,34] However, limitations of this method are still present. First, there are conflicting results on how large of a percent increase is needed to produce positive changes in biomechanical variables. While +10% increases may produce more desired biomechanical change,[32] +5% conditions also produce change biomechanically[32,33] and have had less impact on RPE measures.[32] Additionally, a 7.5% increase has produced biomechanical changes and improved patient rated outcomes,[34] but has been reported as slightly unnatural up to 6-months post-retraining.[238] Due to the range of percentage increases used in the literature, it is difficult to discern how much of an increase is ideal. Within the literature, a metronome is predominately used to reinforce the increased SR, and appear to produce the desired change in SR, so no studies reported an inability of runners to acquire the change..[31-34,81,236,238,249] However, rehabilitation environments that offer autonomy produce better motor learning outcomes.[38] Using self-selected music over a metronome to increase SR may offer many benefits, including enhanced expectancies and autonomy. If music is in fact an alternative to a metronome for SR gait retraining, clinicians and patients could use this method, creating more choice in the rehabilitation environment. Finally, there is a lack of research that has investigated the long-term retention of increased SR after gait retraining. In order to demonstrate that retention of increased SR is possible, more research needs to include long-term follow up testing in their protocol.

In-field Gait Retraining: If gait retraining techniques cannot be generalized to more clinical settings, it is unlikely they have potential to make a large impact on the public health issue that is RRI. One major benefit to SR modification gait retraining is the accessibility of this technique. Several studies have employed what is commonly called “in-field gait retraining” techniques. In-field gait retraining typically utilizes technology, such as a phone or a watch, to provide cueing to the runner and allow them to retrain at the target SR without reporting to a lab or being guided by the researcher. While this strategy cannot be commonly utilized with other forms (kinematic and kinetic) of gait retraining, it can be done easily when selecting to increase SR within the gait retraining protocol.

Willy et al.[30] conducted one of the first in-field gait retraining protocols for high impact runners. The runners in the retraining group were then asked to increase their SR by 7.5% and introduced the technology (Garmin watches and a foot pod) being used for in field- gait retraining and mobile monitoring. The foot pod collected running pace, duration, and spm. The retraining group was able to see this data on the watch in real-time during four out of the eight retraining sessions. Runners were allowed to look at the watch as many times as possible to confirm they were running at their target SR. After 8 in-field retraining sessions, all participants completed a posttest and the retraining group's watches were programmed so SR was no longer visible. Participants were then told to continue their normal running routine for one month while wearing the watch. The retraining group increased their SR and decreased their VLR, peak hip adduction, and eccentric knee joint work per kilometer compared to the control group after the 8 retraining runs. The changes to SR and VLR were retained one month later. Results of this study demonstrate the effectiveness of an in-field gait retraining program. There are significant strengths of this study including the limited time required of the participants and researchers to accomplish biomechanical changes that may decrease injury.

Wang et al.[36] performed a SR modification gait retraining with a commercial phone application. Participants in the retraining group were given access to a metronome phone application, as well. Tempos for each runner in the retraining group were set to 7.5% above the preferred SR. Those in the control group ran using a running application, but not the metronome. The retraining schedule for this study consisted of three outdoor or treadmill running sessions a week with the metronome for 12 weeks. To help achieve compliance, one of the retraining sessions was conducted in group running sessions with the researcher present. During these group running sessions, participants were not given feedback by the researcher. Each time they completed a run, participants could check their average SR through the phone application. SR was increased by 5.7% and impact peaks, VLR, and peak knee flexion angle were decreased in the retraining group after the intervention. This study demonstrated that a cellphone application could confirm that participants were complying to the increased SR and their normal running training volume. Validity data for this application was not reported, which is a significant limitation.

Bramah et al.[81] expanded on the thought of a more "hands off" approach to gait retraining in those with PFP. Runners were then instructed to increase their SR by 10% while being cued with an audible metronome for 5 minutes. The metronome was then removed, and the runner was instructed to maintain the increased SR for 5 minutes with no metronome. Auditory cueing was reintroduced if the researcher determined it necessary. Participants were instructed to use their phone and a Garmin watch to continue using their new gait on their own. Participants were told to use the metronome app during the start of the gait retraining, but then remove it and only monitor their cadence using their watch towards the end of the gait retraining. After 4 weeks of gait retraining, participants were told to continue with their normal running routine without the use of the metronome or watch. A 3-month post-retraining gait analysis was conducted after this period. SR was increased at the 4-week follow up by ~11.2% and ~9.2% at the 3-month follow up when compared to baseline. There were significant decreases in contralateral pelvic drop, hip adduction, and knee flexion at both the 4-week and 3-month follow up compared to baseline. Patient-rated outcomes of pain and function were improved and an increase in total weekly running volume and longest distance run were reported. This study was one of the first studies to demonstrate an in-field gait retraining protocol can produce positive patient-rated outcomes and biomechanical changes in those with PFP.

Brake et al.[58] aimed to determine the feasibility of a 4-week music-based running program on cadence. Runners were given a Garmin watch with the capability to play music. They were also instructed to wear a Garmin HR monitor that measured SR, speed, HR, distance, and altitude gains throughout running. Participants were told to maintain their running volume and choose an outdoor running route with as little obstacles as possible. A baseline test was conducted as the participant ran this selected route without any instructions at their self-selected pace. A non-personalized music playlist was then selected that had a tempo of ~7.5-10% above the preferred SR. The instructions given were to "try and adjust your cadence to the rhythm of the music and keep the running speed roughly equal to the speed of your training sessions without music." A brief practice session was then done with the researcher present and feedback was provided, if needed. Following, the runners were told to continue their training in this way for 8 running sessions. A monitoring phase without the Garmin and music was collected over 12 weeks. There was a significant increase in SR of ~8.5% during the intervention phase when compared to baseline SR. SR remained increased by 7.9% during the monitoring period. HR remained the same throughout all phases of the study. Limitations of this study include the choice to not include self-selected playlists within the intervention and using Garmin technology to carry out the intervention. This study is the first to demonstrate the feasibility of a music-based intervention to increase SR. Results indicate that music is a promising avenue to continue to be explored when the goal is to increase SR without influencing HR. Running biomechanics were not explored in this study, therefore, should be further explored in the future.

Limitations and knowledge gaps of in-field gait retraining: Willy et al.,[30] Bramah et al.,[81] and Brake et al.[58] used Garmin watches and mobile-monitoring devices to conduct their in-field gait retraining protocols. The technology used in this study is more accessible than using lab equipment, but still may not be available for all runners as the additional cost of such equipment could reach over 300 dollars. However, ~85% of Americans already own cell phones.[82] Wang et al.[36] did use cell phone applications to record running volume and SR and to deliver the auditory cueing of a metronome. The results of this study indicate that the use of cell phone applications may provide positive biomechanical changes, while using technology people likely already own. Future research should aim to provide evidence in support of gait retraining conducted with cell phones.

Faded-feedback schedules have been found to enhance motor learning.[252] Wang et al.[36] allowed participants to use a metronome via cell phone application without a faded-feedback schedule, in contrast to other in-field gait retraining protocols.[30,81] Wang et al.[36] reported the SR of the retraining group was increased by 5.7% but was intended to increase by 7.5%. It is possible that the prolonged exposure to the auditory cue that was not gradually faded out led to the gap seen in the target SR and the SR collected post-retraining within this study. The 5.7% increase did accompany positive biomechanical changes, but it would be beneficial to investigate the effects of faded-feedback schedules specifically on SR when using in-field gait retraining. Runners in one of the in-field gait retraining studies[81] maintained the increased SR at long-term follow-ups and reported they didn't use the metronome past the first week. As discussed above, a faded-feedback schedule is thought to improve motor learning. However, the participants in this study retained the new SR and positive biomechanical changes but self-reported not complying to a faded-feedback schedule. There seems to be more room to continue to explore the proper dosage for feedback schedules when using in-field gait retraining protocols.

Compliance of gait retraining: The differences between compliance and adherence are typically overlooked within the sport medicine and exercise literature. For the purposes of this review and this study, compliance will be defined as “the extent to which the patient’s behavior matches the prescriber’s recommendations”.[76] The term adherence refers to “the degree to which behavior corresponds to an agreed plan”.[275] The key difference between compliance and adherence is that adherence involves a more active role in the plan of care while compliance is based predominately on the instruction given by the researcher or clinicians. Hawley-Hauge et al.[276] suggested researchers attempting to measure adherence define adherence using outcomes important to the specific goals of the intervention, which can illustrate the effectiveness of the intervention.[276] Although compliance and adherence are two different constructs, it is logical that compliance be measured using variables relevant to the intended goals of the exercise prescription being given. With that being said, the definition of compliance, in most cases, should include several measures relevant to successful outcomes of the intervention.[276]

There is currently not a consensus for what compliance to gait retraining should be defined as. When examining the gait retraining literature, it may be relevant to define gait retraining compliance using 1) attendance or completion rates (expressed as a percentage),[276] 2) running volume maintenance, and 3) motor performance of the gait retraining prescription. In this section of the review, the focus will be studies on SR gait retraining and compliance to SR gait retraining prescriptions.

Compliance to attending gait retraining sessions or completion of gait retraining programs should be considered relevant to gait retraining prescriptions. Attendance and completion can demonstrate the clinical utility of the prescribed report times. Should attendance and completion be low, it is impossible for the other aspects of compliance to gait retraining protocols mentioned above be observed. To deem attendance and completion reasonable, the two-thirds rule[277,278] may be the most evidence-based cutoff to use. General exercise literature has defined adherence as successful completion of prescribed exercise at least two-thirds of the time.[277] When individuals have participated in two-thirds of suggested exercise sessions, functional improvements and other health-related benefits can be detected.[277,278] Gait retraining protocols aimed to increase SR can be examined for compliance to attendance and completion. In-person gait retraining sessions have reported attendance of to be 100% (10/10 participants attended all sessions)[236] while hybrid in-person gait retraining completion rates are 90% (10/11 participants completed retraining).[34] In-field gait retraining completion rates range from 71-100%[30,36,58,81] Overall, compliance to attendance and completion of gait retraining programs appears to be subjectively reasonable. Using the two-thirds rule,[277,278] attendance and completion of gait retraining sessions would fall above the threshold for functional health-related gains to take place.

Willy et al.[88] noted that participants with the lowest running volume during their gait retraining protocol were the individuals that displayed gravitation towards old gait patterns, perhaps indicating runners who did not maintain their running volume may not have been practicing their new running form. Since practice would be essential to achieving motor learning and retention of new gait patterns,[37] maintained running volume is another variable that can help define compliance to practice of the new gait pattern. Maintenance of running volume has been measured using self-report logs,[81,236] watches[30,58] and cell phone applications.[36] Collecting running volume compliance may clue researchers and clinicians in on how often the runner is training and, potentially, practicing the new gait pattern. However, compliance to the increased SR is also an important aspect of confirming compliance to practice needed for motor learning.

Motor performance compliance could be measured by ensuring the runner is performing the prescribed gait retraining task[37,128] at various time-points throughout the training and after the training has concluded. SR gait retraining studies have used instrumented treadmills[30] and watches[30,58,81] to measure SR throughout and at the conclusion of gait retraining interventions. Studies aimed to increase SR have demonstrated compliance to the increased SR prescription after gait retraining has concluded. Neal et al.[34] noted an increase in SR in all but three participants in the study (compliance to target SR= 70%).[34] Willy et al.[30] used the term adherence for their study. Adherence was defined as maintaining an average in-field SR of at least 5% greater than the baseline preferred SR. There was 75% (12/16 participants) of participants who complied to the prescribed increased SR of about 8.5% higher than baseline. Within the following month after the retraining feedback was completely removed and no direction was given to use new gait patterns, 60% (10/16) participants were still compliant to the previously prescribed increased SR of about 8.4% higher than baseline. Wang et al.[36] did indicate their gait retraining group increased their SR after the retraining period. The researchers excluded participants from the study if an increased SR of 7.5%+ preferred wasn't achieved consistently within the first three weeks of the protocol. However, data was not shared on how many participants were excluded for lack of compliance to the increased SR, and therefore, it is hard to discern the true compliance of the increased SR. Overall, few studies have determined if the increased SR is being complied to by the runners when they are not running with the researcher's guidance. Future research on strategies to ensure that when the runner is running outside of the gait retraining protocol and/or the lab environment would be greatly beneficial to determine compliance of gait retraining.

One interesting observation is the lower rates of completion observed between the in-field gait retraining techniques that used metronome applications (80-83%)[36,81] when compared to the study that did not use a metronome (100%).[30] A common reason for lack of compliance to exercise programs is ignoring the psychosocial needs of an individual when designing exercise programs.[279] Lack of enjoyment is an often identified barrier to physical activity, as well. [78] It is possible that the use of a metronome ignores psychosocial aspects of running, such as enjoyment of the exercise, during gait retraining and is contributing the lack of completion of the intervention. Brake et al.[58] used music, potentially trying to increased enjoyment, and found lower rates of compliance to complete the intervention. These researchers did choose to create researcher-selected playlists, which is not recommended.[56,57] Perhaps the use of music within gait retraining interventions should use a participant-selected playlist and determine if compliance is improved.

Defining compliance as both maintaining the intended running volume and the target SR throughout provides researchers a lot of information about whether the runner is complying to the intended gait retraining goal. Some studies have restricted running volume for their participants,[236] and some have not.[81] In both cases, there were no reports of lack of compliance or maintenance of running volume. Several studies did not specifically report changes in running volume within the SR gait retraining literature.[30,34,36,58] Future studies should aim to determine if compliance to running volume can be influenced by directions of researchers. Additionally, gait retraining studies should begin to report running volume compliance, as it is an important part of overall compliance to gait retraining prescription and motor learning. Further, since runners tend to over-report their running training volume[280] researchers should aim to use technology in gait retraining studies that can acquire both SR and running volume directly.

Summary and knowledge gaps in gait retraining literature: Most gait retraining studies have adopted an 8 session, 2-week faded-feedback schedule,[86-88,233,234,238,249] but this schedule has not been shown to be an evidence-based dosage. Recent evidence indicate researchers may be able to accomplish effective gait alterations without the time-intensive schedule.[32,81,235,253] Since large time commitment may not be possible at many clinical sites, future research should adopt more evidence-based gait retraining schedules. Additionally, the use of auditory feedback has been found to be a more effective strategy for motor learning when compared to visual feedback.[254] Perhaps more research should be conducted on auditory cueing that is also available for the runner outside of the lab.

Gait training methods including but not limited to verbal feedback,[30,36,81,86-88,233-236,238,249] visual feedback,[86-88,233-235] and auditory feedback[31-34,36,81,236-238,249] have been used. Aims of gait retraining have mostly been focused on changing potentially harmful kinematics, decreasing excessive loading (kinetics), and adjusting temporospatial characteristics. A majority of the studies addressing kinematics are aimed to reduce hip adduction[86,88] and alter foot strike angles.[87,238] The literature suggests that kinematic gait retraining is effective, but may be more effective for those runners diagnosed with PFP specifically,[86-88] rather than applicable to runners with other RRI or as a prevention strategy. Kinetic gait retraining protocols have also been effective at reducing loading.[233-235] Also, prospective evidence suggests kinetic retraining has led to a decrease in RRI development.[233] Unfortunately, the methods for kinematic and kinetic gait retraining may have limited clinical utility at this time, as mostly clinically inaccessible forms of feedback were used in these studies. Due to the aforementioned limitations of kinematic and kinetic gait retraining methods, temporospatial gait retraining techniques may be more clinically accessible.

Temporospatial studies aimed to increase SR have been shown to lead to kinematic and kinetic changes.[30-34,36,81,236,237] Fewer long-term follow-up studies have been conducted on gait retraining SR, though. Currently, there are conflicting findings regarding the percent increase that is optimal to create biomechanical changes without creating other performance concerns. While increasing SR 10% above the preferred may bring superior changes biomechanically, one study indicated it also increases RPE when compared to increasing SR 5%.[32] Perceived exertion may be considered a negative expectancy that would inhibit motor learning. Increasing SR has primarily been accomplished through use of a metronome.[31-34,36,81,236-238,249] One recent study to use a music-based protocol to increase SR did not investigate how this impacted running biomechanics nor did they use a self-selected playlist.[58] Therefore, the results of this study can be questioned. Gait retraining experts have indicated using music to acquire changes in SR may be less noxious,[83] but no study has confirmed that music will bring the same positive biomechanical adaptations. As autonomy improves motor learning,[38] using self-selected music as an option to increase SR should be explored in future research.

Overall, many protocols within the gait retraining literature have incorporated motor learning principles, like a faded-feedback schedule,[30,81,86-88,233,234,238,249] utilization of external focus of attention,[238] and the use of auditory versus visual feedback,[31-34,36,81,236-238,249] but these studies have not been grounded in a motor learning theory. Recent evidence suggests that motor learning outcomes can be independently improved by all aspects of the practice environment.[44] Gait retraining studies have catered to some conditions that optimize motor learning, but completely ignored others.[88,235] For example, using a faded-feedback schedule but also including feedback when errors are made[88,235] or adopting an external focus cue but ignoring autonomy of the learner.[30,233] In general, it is possible that gait retraining outcomes can be improved when all aspects of the intervention are supported by the OPTIMAL theory. Future research on gait retraining intervention conceptualized within the OPTIMAL theory should be completed.

Music in Gait Retraining:

In a recent mixed-methods study, gait retraining experts were interviewed regarding techniques they use to increase SR.[83] Some indicated they refrain from the metronome because they believe it to be a more noxious stimulus and even have said they find it annoying.[259] Many experts indicated they have encouraged the use of music or would much rather use music to increase SR.[259] Exercisers have showed a preference towards using music in general[180] with the most common activity performed with music being running.[46] Bood et al.[54] indicated that music produces similar results of SR consistency against a metronome during running. One gait retraining protocol has implemented music to increase cadence successfully with in-field methods but did not investigate running biomechanics.[58] For the sports medicine community, increasing SR is a method employed to decrease loading and harmful biomechanics in hopes to combat RRI, but music hasn’t been shown to be an effective way to change biomechanics yet.

One tool that is not mentioned within the OPTIMAL theory is the use of music for facilitation of motor learning. Physiological evidence has been found to support this intervention to enhance motor learning outcomes, particularly when it comes to gait retraining. Synchronization is a rhythm response describing the stable maintenance overtime of sensorimotor coupling between beat and footfall.[281] Listening to rhythmic auditory cues have been found to increase neural efficiency to facilitate auditory-motor entrainment.[282] Entrainment entails the stable timing between the match of musical stimuli and exercise tempo. For example, entrainment can be observed when running SR is consistently aligned with the tempo of music.[281] Synchronous music can facilitate error correction and execution of precise and accurate movement when rhythm patterns are heard,[283,284] which are two markers to describe the motor learning phase.[37] Automaticity of the movement (less cognitive activity, more motor activity) is a marker of the later phases of motor learning.[37] retraining.[285,286] Further, humans have a natural ability to almost instantly respond to rhythmical qualities of music.[73] In general, humans tend to respond and naturally synchronize movements to the tempo (bpm) of music[74] and runners respond to musical rhythm by synchronizing their SR without even being told to do so.[59,60,70] Therefore, the automatic and intuitive nature of SR synchronization to music tempo during running may aid in motor learning and gait. All of these physiological processes provide further evidence for the use of music to modify SR in gait retraining protocols.

Literature Review Conclusions:

Many variables have been identified to interact and increase risk of RRI.[14] Running biomechanics are consistently cited as underlying causal factor for many variables within the Bertelsen model of RRI etiology.[14] Particularly, increased VLR and hip adduction and decreased knee flexion are the most compelling running biomechanics associated with RRI. For this reason, intervention to alter potentially injurious biomechanics is warranted. Gait retraining has been determined as an intervention to prevent and treat RRI. Therefore, methods of gait retraining should be explored to discover the most effective ways to alter running biomechanics that may lead to RRI. Gait retraining is a form of motor learning and thus, should cater to motor learning principles.

The OPTIMAL theory of motor learning highlights strategies that can be used to create ideal practice conditions for motor learning to occur from a neurophysiological and psychological perspective. Using this framework, it is essential to create practice environments that cater to enhanced expectancies, autonomy, and external attentional focus. Strategies to enhance expectancies are vast, but no studies have explored how music can enhance expectancies and optimize motor learning. There is ample evidence to suggest that music can enhance expectations by 1) increasing positive affect, 2) improving physiological function, and 3) decreasing perceptions of exertion and fatigue when exercising. Autonomy is also essential to optimizing motor learning. Even incidental choices within the practice environment have produced better motor learning outcomes. Still, sport medicine motor learning intervention rarely allow for autonomy in practice environments. Using a self-selected music playlist can honor autonomy and potentially create a positive impact on motor learning, but no studies have explored this. Therefore, research should explore the effects of music to enhance expectancies and autonomy on motor learning.

Gait retraining focuses have included kinematic and kinetic alterations. Largely, the results of these studies cannot be generalized to clinical environments as the technology used was bound to research labs. Increasing SR has been found to create kinematic and kinetic changes without these limitations. Gait retraining protocols have also almost exclusively used a similar 8-session, 2 week, faded-feedback protocol. However, this time commitment may not be possible at many clinical sites and emerging evidence indicates motor learning of new gait patterns can be produced in less time. Increasing SR appears to be a very intuitive strategy for runners and can be carried out in a more “hands-off” manner with inexpensive technology. One caveat to increasing SR is that studies have only explored the biomechanical effects using a metronome. As stated, music brings many benefits to exercise and is often preferred during running. Since music and metronomes provide the same auditory cue in bpm, it is reasonable to assume they both would work effectively to retrain injurious biomechanics in gait retraining protocols. Additionally, the use of music for gait retraining likely would improve motor learning according to the OPTIMAL theory. It has yet to be shown that music is an effective method for increasing SR and improving potentially harmful running biomechanics. Research should be completed to determine if music and a metronome produce similar effects on running biomechanics and compliance to gait retraining protocols.

Chapter 3: Methods

The following methods chapter is organized to present information on the study design, participants, measurements, procedures, and statistical analysis. The study design, participants, and measurement sections will include descriptions and background on the study design, participants, measurements, and data processing pertinent to the study. The procedures section will include the chronological process of events used for the study.

Study Design and Setting:

This was a longitudinal cohort study. Research activities were performed both within and outside of the research laboratory setting. The setting for the study was a midwestern university and surrounding community between the months of December and March. Figure 6 displays the full study protocol used for this study. Participants were randomly allocated to groups using random number allocation, and the researcher was not aware of the group assignment until the intervention began. Sex assigned at birth was used to counterbalance groups because running biomechanics[108,118,291] and music to movement coordination[65] have been previously found to vary between sexes.

Participants:

Sample Size: A power analysis based on previously published data[54] and expected change in RPE (d = .30) was performed with G*power. 24 total participants were needed to reach a power of >.80 for this research study. To account for a 20% dropout rate, we recruited 30 participants. A detailed description of the power analysis process and a review of sample sizes used in similar studies is included in Appendix A.

Recruitment: Participants were recruited by word of mouth (social media posts/flyers) and announcements at various locations on the campus of University of Wisconsin-Milwaukee including but not limited to the Klotsche Center exercise facility, Multicultural Student Centers, and Student Union in attempt to diversify the participant sample. Recruitment was also conducted in various locations across the greater Milwaukee area to ensure a sample that was representative of the area was obtained. Recruitment materials are included in Appendix B.

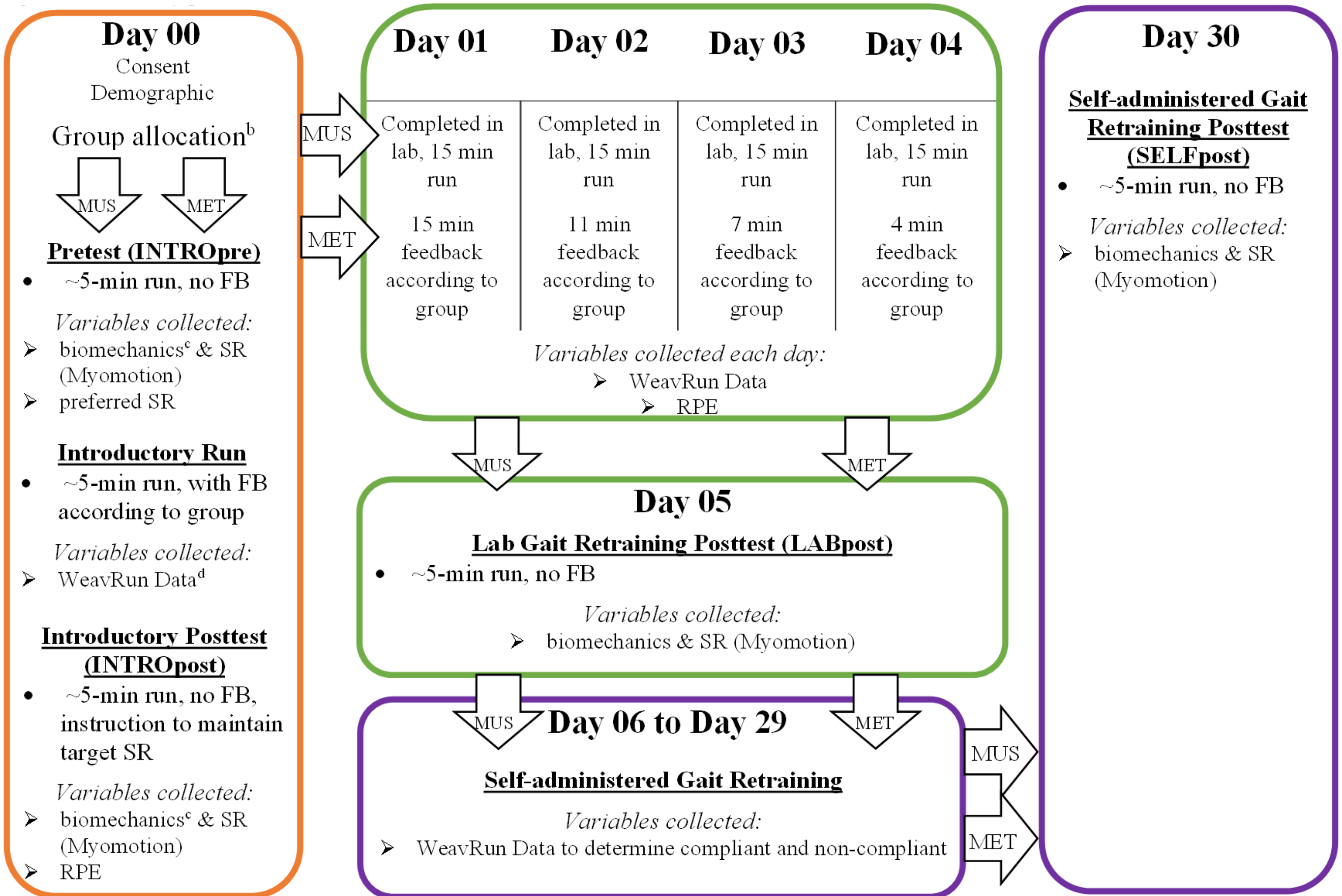
Inclusion and Exclusion Criteria: A screening for inclusion and exclusion criteria was conducted via phone prior to scheduling the first lab session. (Appendix C) To be eligible for the study individuals had to meet the inclusion criteria of 1) male or female rearfoot strike runner,[287] 2) ages 18-50,[112,113,115,288] 3) maintain at least 5mi of mileage per week, 4) have access an iPhone/iPod for the duration of the study. Exclusion criteria included those 1) that have a self-reported history of medical conditions that may impair balance (i.e. concussion, neurological impairments, etc.,[81,87] 2) are pregnant,[87] 3) have an implanted pacemaker device, 4) have a current injury in which they cannot perform the running required for the study,[31-33,36] 5) adopt a forefoot strike pattern, and/or 6) have a preferred SR ≥ 170 steps/min.[289] Participants were also instructed to remain in the same shoe for the duration of the study, if eligible.

Measurements:

The measurements used to achieve the aims of the study are described below and then referenced in the protocol section in chronological order.

Demographic Information: A table explaining the purpose of each demographic variable is included below (Table 2). Age, height, weight, and race were collected to characterize the sample. Gender identity was collected to characterize the sample more appropriately for those

Figure 6. Full Study Procedures



[a]Orange =time points relevant to Aim 1, green =time points relevant to Aim 2, purple =time points relevant to Aim 3; [b]Experimental protocol same for each group with exception of type of auditory feedback; [c]Data include peak positive tibial acceleration, hip adduction and knee flexion; [d]Data include target SR and actual SR of participant at throughout run (measured by time in seconds)

who identify outside of their sex assigned at birth. Dominant limb was defined as the limb the participant would choose to kick a ball with and was for data collection and analysis. Musical background was collected in order to describe the sample similar to previous studies.[59]

Table 2. *Demographic information purpose and rationale*

Information	Purpose of collecting	Rationale
Age	Descriptive	• Characterizing the sample • Confirming eligibility • Examining for differences at INTROpre to report differences
Height	Descriptive	• Characterizing the sample • Examining for differences at INTROpre to report differences
Weight	Descriptive	• Characterizing the sample • Examining for differences at INTROpre to report differences
Race	Descriptive	• Characterizing the sample • Examining for differences at INTROpre to report differences
Gender identity	Descriptive	• Characterizing the sample (request of IRB of university) • Examining for differences at INTROpre to report differences
Sex assigned at birth	Descriptive and counterbalancing the groups	• Characterizing the sample (request of IRB of university) • Counterbalancing the groups
Dominant limb	Used to for data collection procedures	• Determining analysis limb
Musical background (playing an instrument, dance, etc.)	Descriptive	• Characterizing the sample

Self-reported running volume (in miles)	Descriptive and used to define compliance	• Characterizing the sample • To define one component of compliance to the self-administered gait retraining program

Inertial Measurement Unit (IMU) Measurements: Treadmill running was selected for this study to collect continuous running biomechanical data and so instruction and auditory cueing could be given as needed throughout the study. Temporospatial and kinematic variables collected during treadmill running have been reported to be comparable to temporospatial, kinematic, and kinetic variables collected during overground running.[292]IMU data were recorded using the MyoMotion system (Noraxon USA, Scottsdale, AZ) at 200Hz while running on the treadmill. Myomotion IMUs were placed on the self-reported dominant limb pelvis, lateral mid-thigh, and distal medial tibia, according to the manufacturer recommendations (Figure 7). A multi-pose calibration of the MyoMotion system was conducted for each participant as shown in Figure 8. After collection, data were filtered through the Myomotion system to eliminate noise and correct drift. All Myomotion IMU data was then directly exported to Excel so data could be properly processed. First, tibial acceleration of the dominant limb from the IMU sensor placed on the shank (distal medial tibia)[298] was used to identify gait events. The stance phase was identified as the moment of initial contact (IC) to the moment of toe-off (TO). IC was defined similar to previous studies as the minimum acceleration before the peak tibial acceleration.[299] TO was defined as the minimum acceleration after the second local peak occurring after PPA.[299]

<u>SR:</u> SR was determined by multiplying the number of IC points by the number of seconds of the collection time (~10 seconds) divided by 60 (e.g, $\frac{60\ seconds}{10.255\ seconds} \times 12\ contacts$). SR was extracted from the INTROpre, INTROpost, LABpost, and SELFpost timepoints.

PPA: PPA was defined as the maximum vertical tibial acceleration identified during the stance phase (in units of acceleration due to gravity (gs)). PPA was extracted from the INTROpre, INTROpost, LABpost, and SELFpost timepoints.

Peak Stance Phase Hip Adduction: The joint angle of interest was dominant limb peak stance phase hip adduction angle (peakHIPADD), which has been associated with RRI,[15,18,23,24,94,300,301] and was defined as the maximum hip adduction (in degrees) occurring within the stance phase (IC to TO). PeakHIPADD was extracted from the INTROpre, INTROpost, LABpost, and SELFpost timepoints.

Figure 7. *IMU Sensor placement*

Figure 8. *Calibration Position*

Rating of Perceived Exertion Measurement: To measure ratings of perceived exertion the Borg rating of perceived exertion (RPE) scale[295] (Appendix H) was used. The Borg RPE scale is a consistent variable used within studies on running biomechanics,[32] motor learning,[42] and music and exercise.[54,68] The Borg RPE scale[295] is a 15-point numerical and verbal scale ranging from “no exertion” at all to “absolute maximum exertion”. Scale instructions, as written by Borg et al.[295] were read before the introductory run begins in order to ensure the participant understood the scale. When using the Borg RPE scale,[295] participants were presented with numerical choices of numbers 6-20, where 6 is considered “no exertion at all” and 20 is considered “maximal exertion”. The Borg RPE scale is the most widely used instrument to measure perceived exertion[269] and was designed to account for physiological aspects of exercise and exertion, particularly HR and workload and psychological constructs, such as affect, as well.[295] Although the Borg Category-Ratio (values 1-10) and the Borg RPE scale (values 6-20) have demonstrated an interchangeable relationship,[296] the Borg RPE (values 6-20) was selected because this is the original scale and has been suggested as the best for gauging perceived exercise intensity in sports and rehabilitation.[179] Conversely, the Borg Category-Ratio is recommended when identifying symptoms such as difficulty breathing and pain.[179] Similar studies have assessed perceived exertion after shorter durations of running with music and indicated most participants did have slight changes in perceived exertion even after short durations of running.[59,297]

Borg RPE scale values were used to calculate RPE change scores between the in-lab gait retraining sessions (Day 01- Day 04) and the INTROpre timepoint (Day 00). All RPE change scores were calculated as follows: Day 01 RPE - Day 00 RPE, Day 02 RPE - Day 00 RPE, Day 03 RPE – Day 00 RPE, and Day 04 RPE - Day 00 RPE. RPE change scores were then used to operationally define expectancies within the context of the study. A negative RPE change score (e.g., 13 – 17 = -4) indicated the runner felt less exerted and was considered a positive or enhanced expectancy within the study. A positive RPE change score (e.g., 13 – 6 = 7) indicated the runner felt more exerted and was considered a negative expectancy within the study.

WeavRun© Phone Measurement: Weav Run© is a phone application for Apple product users. Weav Run© allows the runner to choose a target bpm for each run and collects running-related data while the individual runs. Through a collaboration, features, including a metronome track and a data export feature, were added to the Weav Run© app specifically for the study. Weav Run© data includes time in seconds, song title and artist currently playing, location (latitudinal and longitudinal coordinates), run distance in meters, the target SR, and the detected SR. The variables of interest that were used to operationally define measures (described below) were 1) detected SR, or SR measured via the Weav Run© phone application and accelerometer measured throughout runs, and 2) running distance, or the meters measured via the Weav Run© phone application and standard global positioning technology throughout runs.

Time to acquisition: The first measure of interest from Weav Run© was called time to acquisition. Time of acquisition was calculated as the time in seconds the detected SR of the runner throughout the intervention run between the INTROpre and INTROpost on Day 00 was within +/- two steps per minute of the target SR calculated for the runner for at least 10 consecutive seconds. There are no definitive criteria to indicate acquisition of increased SR within the literature. Therefore, the definition for time of acquisition within this study was based on 1) the standard error of measure calculated for the Weav Run app SR data (+/- 2 steps per minute) and 2) pilot data indicating that most participants who acquired the target SR for 10 seconds or greater maintained the target SR for the duration of the introductory run with minimal fluctuations.

Compliance: It has been suggested that compliance and/or adherence should be defined according to several measures relevant to successful outcomes of the intervention.[276] There is currently not a consensus for what compliance to gait retraining is. Compliance to running volume maintenance and motor performance (performing the increased SR) would be relevant to outcomes of the gait retraining intervention used in this study, and what the definition of compliance was based on. Therefore, the second measure of interest from Weav Run© data was compliance. This study operationally defined compliance based on the Weav Run data being collected during the self-administration gait retraining. Detected SR and running distance (in miles) was measured for each run taken by all runners throughout the self-administered gait retraining phase. Average detected SR was calculated for each run. The running distance of each run was recorded. Then, the average detected SR and the running distance for each run was averaged across weeks. To compute a single monthly average of SR and running distance, the mean of the average detected SR and running distance for each week was then averaged across the month. The monthly average SR had to be within ± 2 spm of the target SR ***AND*** average running distance had to be at or above the self-reported average running distance collected to be deemed compliant. When the monthly average SR was outside of ± 2 spm of the target SR ***AND*** the average running distance was below the self-reported average running distance collected, the participant was deemed non-compliant.

Procedures

Written informed consent was obtained prior to beginning testing as approved by the Institutional Review Board at University of Wisconsin-Milwaukee (Appendix D). Prior to demographic information being collected (Appendix E), all the eligibility criteria were reviewed and confirmed, which included a brief foot strike pattern screening. The participant was instructed to run on the treadmill at a self-selected pace while the researcher visually confirmed[290] the participant adopted a RFS pattern. Self-reported average weekly running volume was collected to determine eligibility and provide information relevant to determining compliance during later stages of the study. Once deemed eligible, participants in both groups were instructed to Weav Run© using a link specific to study participants. Those allocated to the MUS group were asked to select approximately 20 minutes of music they would prefer to run to throughout their run from the options of songs in the app (directions included in Appendix F).[56,57] Research suggests using participant-selected music versus researcher-selected music to avoid Hawthorne effect,[56] to account for personal and situational factors that dictate music preference and response,[52,56] and to optimize motor learning outcomes through participant autonomy.[38] The MET group only used the playlist with a preloaded metronome set to their target SR (directions included in Appendix G).

Introductory Pretest (INTROpre) Data Collection: The participant then completed a moderate, self-selected walking or jogging pace warm-up on the treadmill for two minutes. The participants began running at a self-selected speed typical to their usual training speed. After five minutes at this speed, the researcher recorded 3D biomechanical data for 10 seconds. The researcher also determined the participant's preferred SR by counting bilateral foot strikes for 30 seconds and multiplying by two.[293] The researcher then calculated the target SR ((preferred SR X 5%) + preferred SR= target SR).

Introductory Run: An introductory run to the increased target SR was then performed. The participant was told to stop the treadmill. Arm bands were placed on the right upper arm and the participants were instructed to place one headphone in their ear and connect to their device. The participant was then asked to set their SR on their device, turn the volume up,[294] and start the auditory cue (MET or MUS). The researcher was wearing the other headphone to give appropriate instruction to the participant throughout the introductory run.

Verbal instructions: This study used autonomy-supportive or neutrally phrased and primarily positive verbal instruction for both the MUS and MET group, as recommended by the OPTIMAL theory[38] (Table 3). This instruction was also designed to direct the attention of each group (MUS and MET) externally by indicating they should focus on moving according to an external auditory cue (Table 3). For the MET group, participants were given verbal instructions including “try to match your foot strikes to the beats of the metronome”. For the MUS group, participants were given verbal instructions including “try to match your foot strikes to the beats of the music”. Once it was clear the participant understood the instructions, they were instructed to begin running at the same self-selected speed as at the INTROpre and continue to run for approximately 5 minutes with the auditory cueing. Additional verbal instruction developed based on pilot testing was given approximately halfway through the introductory run (at ~2.5 minutes) to each participant. The additional verbal instruction was positively phrased as much as possible and informed participants they were on target or informed them they were not on target so they could make the appropriate corrections. (Table 3). After five minutes, the auditory cue was removed, and the participant was instructed to continue running at the target SR without stopping the treadmill.

Table 3. *Instruction and description of OPTIMAL principles*

Full instruction	“Here is the part when we are going to increase your step-rate by 5%. To aid you in increasing your step-rate we use the Weav Run app and the beats of the *type of auditory cue*. I have calculated your preferred step-rate to be at ___ *let the participant hear what that sounds like* so your target step-rate is now ___ *let the participant hear what that sounds like*. A tip that may help you with this task is to try and match your footfalls to the beats (tempo) of the *auditory cue*, like so

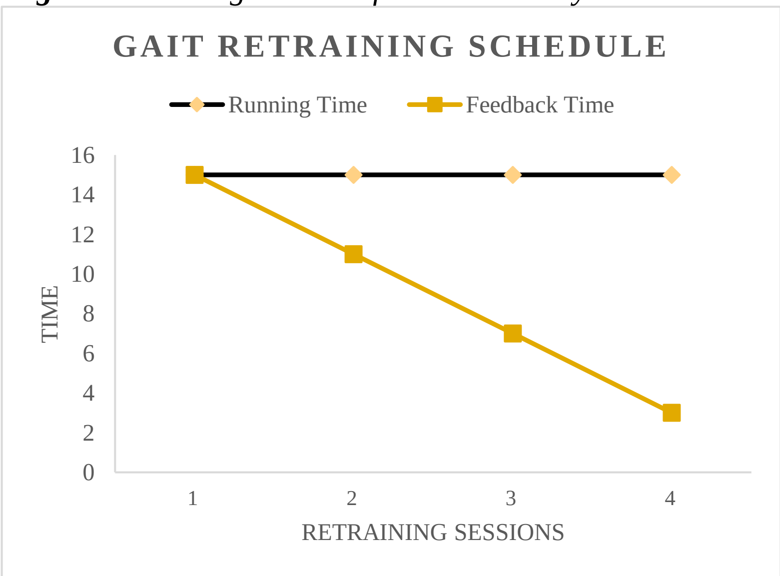
	demonstration of researcher marching to the target step-rate while the audible cue is playing. Do you understand the goal of the task? Do you have any questions? Throughout this part, I will let you know how you are doing on the task periodically.	
OPTIMAL principle	**Strategy**	**Verbal Direction**
Autonomy	Autonomous/Neutral instruction	"A tip that may help you with this task…"
External Focus	Directing attention externally to the auditory cue	"match your footfalls to the beats (tempo) of the *auditory cue*"
Additional instruction if more clarification is needed	• "You may find it helpful to take smaller steps/strides in order to match your footfalls to the beats." • "You may think of increasing your step-rate as taking shorter steps while you run in reference to the auditory cue beats" • "You may think of increasing your step-rate as landing with your heel under your hip in reference to the auditory cue beats."	
OPTIMAL principle	**Strategy**	**Verbal Direction**
Autonomy	Autonomous/Neutral instruction	"You *may* find it helpful…"
External Focus	Directing attention externally to the auditory cue	• "…match your footfalls to the beats (tempo) of the *auditory cue*" • "…in reference to the auditory cue beats"
Additional instruction given throughout the running trials	• "You're doing great, but really focus on those beats." • "Your step rate is looking really good!" • "Not quite there, but almost. You can try *any of the above cues*… Yes, looks good now." • "You seem to be right on target." • "You seem to be slightly faster/or slower than target, but that's okay. You can try *any of the above cues*."	
OPTIMAL principle	**Strategy**	**Verbal Direction**
Enhanced expectancies	Positively phrased, yet corrective feedback	• "You're doing great…" • "Your step rate is looking really good!" • "…but that's okay"

		• "…but almost"

Introductory Posttest (INTROpost) Data Collection: Five minutes after the auditory cueing was removed, the researcher recorded 3D biomechanical data for 10 seconds in the same manner as the INTROpre. The participants were then asked to rate their perception of exertion with the RPE scale[295] directly after the conclusion of the INTROpost. Before the participant left, further instruction for the WeavRun© app and gait retraining sessions were given (Appendices F & G).

Gait Retraining Sessions (Days 1-4): The first gait retraining session was completed on a different testing date from the INTROpre and INTROpost timepoint (within 2.73 ± 1.26 days). Participants were instructed to wear the same running shoes as the INTROpre for all the in-lab gait retraining sessions and posttests. A gait retraining schedule consisting of four sessions of 15-minute runs using a faded-feedback design[252] of the auditory cueing (MET or MUS) then took

Figure 9. *Running time and feedback time by session.*



place. Figure 9 depicts the schedule of days and time with auditory cueing. All gait retraining sessions were conducted within a period of 6.76 ± 4.29 days. Four individual sessions of in-lab gait retraining was selected based on evidence.[253] Participants were allowed to run outside of the in-lab gait retraining sessions but, if they chose to, were instructed to use the WeavRun© app set to the target SR being used within the in-lab gait retraining sessions. To begin the in-lab gait retraining sessions, universal arm bands to hold the participant's device were placed on the right upper arm. The participant was instructed to place one headphone in their preferred ear and connect to the device. The researcher wore the other headphone to give appropriate feedback for the participant throughout the session. The participant was then asked to set their SR to the same target SR as the introductory run on their device, turn the volume up, and start the auditory cue (MET or MUS). The phone was then placed in the arm band. For the MET group, participants were given verbal instructions including "try to match your foot strikes to the beats of the metronome". For the MUS group, participants were given verbal instructions including "try to match your foot strikes to the beats of the music". This study used autonomy-supportive or neutrally phased and primarily positive verbal instruction for both the MUS and MET group, consistent with the OPTIMAL theory (Table 3). Instruction was also designed to direct the attention of each group (MUS and MET) externally by indicating they should focus on moving according to an external auditory cue (Table 3). The participant was then instructed to begin running at the same self-selected speed as the INTROpre. Additional verbal instruction based on pilot testing was developed. All additional instruction positively phrased to the greatest degree possible and given every 2.5 minutes to each participant and informed participants that they were on target or informed them they were not on target so they can make the appropriate corrections (Table 3) The participants were then asked to rate perception of their exertion with the RPE scale[295] after the conclusion of each gait retraining session.

Day 5, In-lab Gait Retraining Posttest (LABpost) Data Collection: The LABpost was completed on a subsequent testing date from the last in-lab gait retraining session (within 2.93 ± 2.94 days). Average weekly running volume was updated for the current week to ensure that compliance was appropriately defined for the next phase of the study. The researcher gave no instruction to the participants regarding their gait and no auditory cueing was provided. The runner began to run at the same self-selected pace used throughout the duration of the study. After 5 minutes of running at this pace, 3D biomechanical data was collected for 10 seconds. Before the participant left, further instructions for the Weav Run app and gait retraining prescription for the next month were given. The "export" feature on Weav Run (Appendix F & G) and expectations for the remainder of the study were reviewed.

Days 6-29, Self-Administered Gait Retraining: After the LABpost, participants were instructed to maintain their new gait pattern using the Weav Run app during their normal running routine outside of the laboratory (Appendix F & G). Participants were instructed to use the armbands and Weav Run app in the same way they have been during the guided in-lab gait retraining sessions. Participants could choose to run on the treadmill or overground, according to their normal preferences and were instructed to maintain their typical running routine and mileage. Instructions for the Weav Run application and the self-administration phase were printed and emailed to the participant. (Appendix F and G). The participant was instructed to export their data directly from the Weav Run application to a file uploader within the survey (Appendix I) coded with their participant identification number. On a weekly basis, the researcher emailed participants in this phase of the study to remind them to be recording and exporting their data. This email also included a link to a brief survey to ask about Weav Run use throughout the week. (Appendix I).

Day 30, Self-administered Gait Retraining Posttest (SELFpost) Data Collection: The SELFpost was completed within 28.33 ± 2.76 days of the first day of the self-administered gait retraining phase. The researcher gave no instructions to the participants regarding their gait and no auditory cueing was provided. The runner began to run at the same self-selected pace used throughout the duration of the study. After 5 minutes of running, 3D biomechanical data was collected for 10 seconds.

Statistical Analysis:

Participant Characteristics: Independent t-tests between groups were conducted to report and describe how similar the groups were in age, height, weight, musical background, and self-reported average weekly mileage. There is not sufficient evidence that any of these variables would be a significant confounder, so no adjustments were planned for the final analysis. The intention to treat approach was selected a-priori,[30] however, no participants were allocated to a group that did not complete the study.

Aim 1: A 2 X 4 multivariate repeated measures analysis of variance was performed to determine the differences in dependent variables between each group (MET vs MUS) by time (INTROpre, INTROpost, LABpost, SELFpost). Alpha was set at .05. In the event of a significant interaction for any variables, follow up testing was performed using a Bonferroni corrected alpha (.025 for the 2 groups being examined and .0125 for the timepoints being examined). If a significant interaction effect was not found, the main effects of time and group were examined and appropriate follow-up tests (pairwise comparisons) for each dependent variable were conducted.

<u>SR:</u> It was hypothesized there would be a significant interaction between group and time where differences in SR between timepoints depended on group. Further follow

up tests examining the differences between the INTROpre and INTROpost and then between the INTROpost and the subsequent posttest timepoints (LABpost, SELFpost) separately for each group (MUS, MET) were expected to reveal the MUS group SR significantly increased from INTROpre to INTROpost and did not significantly change from the INTROpost to LABpost or SELFpost timepoints. It was also expected that the MET group SR significantly increased from INTROpre to INTROpost and did not significantly change from INTROpost to LABpost but decreased from the INTROpost to at the SELFpost timepoint.

PPA: It was hypothesized there would be a significant interaction between group and time where differences in PPA between timepoints depended on group. Further follow up tests examining the differences between the INTROpre and INTROpost and then between the INTROpost, and the subsequent posttest timepoints (LABpost, SELFpost) separately for each group (MUS, MET), were expected to reveal the MUS group PPA significantly decreased from INTROpre to INTROpost and did not significantly change from the INTROpost to LABpost or SELFpost timepoints. It was also expected that the MET group PPA significantly decreased from INTROpre to INTROpost and did not significantly change from INTROpost to LABpost but increased from the INTROpost to at the SELFpost timepoint.

peakHIPADD: It was hypothesized there would be a significant interaction between group and time where differences in peakHIPADD between timepoints depended on group. Further follow up tests examining the differences between the INTROpre and INTROpost and then between the INTROpost, and the subsequent posttest timepoints (LABpost, SELFpost) separately for each group (MUS, MET), were expected to reveal the MUS group peakHIPADD significantly decreased from INTROpre to INTROpost and did not significantly change from the INTROpost to LABpost or SELFpost timepoints. It was also expected that the MET group peakHIPADD significantly decreased from INTROpre to INTROpost and did not significantly change from INTROpost to LABpost but increased from the INTROpost to at the SELFpost timepoint.

Aim 2: To assess group differences, change scores between baseline RPE (Day 00) and each gait retraining session (Days 1-4), a 2 X 4 repeated measures analysis of variance was used. Alpha was set at .05. I hypothesized there would be a main effect of group for RPE change scores. Further follow up tests examining the differences between each gait retraining session timepoint separately for each group (MUS, MET) were expected to reveal RPE change score was larger and in the positive direction (greater perceived exertion) in the MET group when compared to the MUS group, regardless of time point.

Aim 3: There were less than five expected frequencies in the cross-tabulation table between group and compliance, so Fisher's exact test examining the association between group (MUS and MET) and compliance (compliant and noncompliant) was performed. Alpha was set at .05. Examination of an odds ratio was then computed to determine the likelihood of compliance between groups. I hypothesized there would be an association between group and compliance and the MUS group would demonstrate higher likelihood of compliance when compared to those in the MET group.

Table 4. Summary of statistical processes used in this study based on aim and research questions.

Aim	Research question	Statistical Test	Outcome Measures	Hypothesis
Aim 1	Are there differences in SR and running biomechanics between a group that uses a music auditory cue and a metronome auditory cue across the phases of a gait retraining protocol?	2 (group) X 4 (time) Multivariate Repeated Measures ANOVA *If interaction, pairwise comparisons examined with Bonferroni correction*	SR, PPA, peakHIPADD	Group*time interaction • Δ in SR, PPA, peakHIPADD across time depend on group. Pairwise comparisons show: • **SR:** MUS group SR ↑ from INTROpre to INTROpost and no Δ from INTROpost to LABpost or SELFpost; MET group SR ↑ from INTROpre to INTROpost and no Δ from INTROpost to LABpost but ↓ from INTROpost to SELFpost. • **PPA:** MUS group ↓ PPA from INTROpre to INTROpost and no Δ from INTROpost to LABpost or SELFpost timepoints; MET group ↓ PPA from INTROpre to INTROpost and no Δ from INTROpost to LABpost but ↑ from INTROpost to SELFpost. • **peakhipADD:** MUS group ↓ peakhipADD from INTROpre to INTROpost and no Δ from INTROpost to LABpost or SELFpost timepoints; MET group ↓ peakhipADD from INTROpre to INTROpost and no Δ from INTROpost to LABpost but ↑ from INTROpost to SELFpost.
	How long does acquisition of target SR take for a group that uses a music auditory cue and a	Exploratory, descriptive statistics	Time in seconds until target SR is maintained for 10 consecutive seconds derived from	No hypothesis associated, exploratory in nature

	metronome auditory cue?		Weav Run application during introductory run	
Aim 2	Do change scores of RPE from baseline and RPE from each gait retraining session (4 total change scores) differ between a group that uses a music auditory cue and a metronome auditory cue?	2 (group) X 4 (time) Repeated Measures ANOVA *If interaction, pairwise comparisons examined with Bonferroni correction*	Change scores of RPE from baseline and RPE from each gait retraining session	Main effect of group for RPE change scores at regardless of time. Pairwise comparisons show: • MET group RPE change larger in magnitude and positive (indicating larger increases in RPE when compared to MUS group).
Aim 3	Is compliance and group associated? Are those that use a music auditory cue more likely to be compliant to self-admin gait retraining than those that use a metronome auditory cue?	Fischer's Exact test, with odds ratio	Group and dichotomous compliance	Group and compliance are be associated; those in the MUS group would be more likely to comply to the self-administered gait retraining than those in the MET group.

Chapter 4: Results

Participant Characteristics: Descriptive information for the participants by group can be found in Table 5. The two groups (MUS and MET) did not differ based on age (p = .47), height (p = .10), weight (p = .17), or average running mileage per week (p = .85).

Specific Aim 1 Assumptions: Visual inspections of box plots and Q-Q plots of all dependent variables (SR, PPA, peakHIPADD) by group at each time point did not reveal obvious outliers. The skewness and kurtosis values of each dependent variable by group at each time point further confirmed the data did not violate any assumptions of normality. Levene's test of Equality of Error Variances for the dependent variables did not indicate a violation of the assumptions of homogeneity between groups. Mauchly's Test of Sphericity for the dependent variables (SR and PPA) did not indicate a violation of the assumption of sphericity (Mauchly's W(2) = .78, p = .25 and Mauchly's W(2) = .79, p = .27, respectively) across timepoints. For peakHIPADD, Mauchly's Test of Sphericity did indicate a violation of the assumption of sphericity (Mauchly's W(2) = .54, p = .006). Since the assumption of sphericity was violated for peakHIPADD, it was reasonable to doubt the assumption was met for the SR and PPA variables, as well. In addition, the small sample size within the study informed the choice to use a multivariate repeated measured analysis of variance to compare all dependent variables across time points (INTROpre, INTROpost, LABpost, SELFpost) between groups (MUS, MET).

Specific Aim 2 Assumptions: Visual inspections of box plots and Q-Q plots for RPE change scores by group at each time point did not reveal obvious outliers. The skewness and kurtosis values of each RPE change score indicated a reasonably normal distribution of the data. Levene's test of Equality of Error Variances for the dependent variables did not indicate a violation of the assumptions of homogeneity between groups. Mauchly's Test of Sphericity did not indicate a violation of the assumption of sphericity (Mauchly's $W_{(5)}$ = .771, p = .224) across timepoints.

Specific Aim 3 Assumptions: The assumptions for the Chi-square test for independence of two categorical variables was met, however, one cell (metronome group, compliant) within the 2 X 2 table had lower than 5 expected frequencies. For this reason, a Fisher's Exact Test was performed instead.

Table 5. *Participant Descriptive Information*

Age (years)	Mean	SD	Range	p-value
Total (*N* = 30)	29	7.49	19 - 48	
MUS (*n* = 16)	29.94	8.01	19 - 48	.47
MET (*n* = 14)	27.93	6.99	19 - 46	
Height (m)	Mean	SD	Range	p-value
Total (*N* = 30)	1.73	.10	1.56 – 1.98	
MUS (*n* = 16)	1.71	.08	1.56 – 1.85	.10
MET (*n* = 14)	1.76	.10	1.65 – 1.98	
Weight (kg)	Mean	SD	Range	p-value
Total (*N* = 30)	70.23	14.07	52.61 – 114.74	
MUS (*n* = 16)	66.92	7.51	55.78 – 79.37	.17
MET (*n* = 14)	74.02	18.66	52.61 – 114.74	
Average Running Mileage (miles)	Mean	SD	Range	p-value
Total (*N* = 30)	12.30	10.48	5 - 40	
MUS (*n* = 16)	12.69	11.28	5 - 40	.85
MET (*n* = 14)	11.93	9.88	5 - 40	
Preferred SR	Mean	SD	Range	p-value
Total (*N* = 30)	163	6.07	148 - 170	
MUS (*n* = 16)	163	5.44	152 - 170	.94
MET (*n* = 14)	163	6.94	148 - 170	
Race	Black/African American	Asian	Hispanic/Latinx	White
Total (*N* = 30)	3%	3%	3%	91%
MUS (*n* = 16)	0%	6%	0%	94%
MET (*n* = 14)	7%	0%	7%	86%
Sex assigned at birth	Female	Male		
Total (*N* = 30)	60%	40%		
MUS (*n* = 16)	63%	37%		
MET (*n* = 14)	57%	43%		
Gender Identity	Woman	Man		
Total (*N* = 30)	60%	40%		

MUS (*n* = 16)	63%	37%
MET (*n* = 14)	57%	43%
Musical Background	Yes	No
Total (*N* = 30)	53%	47%
MUS (*n* = 16)	56%	44%
MET (*n* = 14)	50%	50%

Specific Aim 1:

Specific Aim 1 was to compare differences in SR and running biomechanics between the MUS and MET groups during the phases of a temporospatial gait retraining protocol (INTROpre, INTROpost, LABpost, SELFpost).

Hypothesis 1A (SR): I hypothesized there would be a significant interaction between group and time where changes for SR over time would depend on group. I expected the MUS group SR would significantly increase from the INTROpre to INTROpost and not change further at the LABpost or the SELFpost. I also expected the MET group SR would significantly increase from the INTROpre to INTROpost and not change further at the LABpost but decrease at the SELFpost.

Results of Aim 1A (SR): Results of the 2 X 4 multivariate repeated measures ANOVA indicated no significant interaction ($F_{(9,336)} = .86$, $p = .56$, $n^2_p = .02$) or a main effect of group ($F_{(3,110)} = 1.63$, $p = .19$, $n^2_p = .04$). However, a statistically significant main effect of time was found ($F_{(9,336)} = 4.38$, $p < .001$, $n^2_p = .10$). Follow up tests of pairwise comparisons for timepoints were conducted using a corrected alpha of .0125. Pairwise comparisons identified a significant increase in SR between the INTROpre and INTROpost timepoints ($p <.001$) (Table 6). To examine the magnitude of change in SR further, the average percent increase in SR from the INTROpre to INTROpost was calculated. From the INTROpre to INTROpost there was an increase in SR of ~4.6% for the MET group and ~5.5% for the MUS group (Table 7). There were no significant differences between the INTROpost and LABpost ($p = .20$). The average percent increase in SR from the INTROpre to LABpost was ~7% for the MET group and was ~6.2% for the MUS group. There were also no significant differences between the INTROpost and SELFpost ($p = .72$) timepoints. The average percent increase in SR from the INTROpre to

SELFpost was ~5.4% for the MET group and was ~5.5% for the MUS group. These results indicate that there were increases in preferred SR between the INTROpre and INTROpost regardless of group, and these increases in SR were maintained at each of the following posttests regardless of the auditory cueing runners were given (group).

Table 6. *SR by timepoint results*

Timepoint	Mean (spm) ± SD	Mean Difference	p-value
INTROpre	163 ± 6.19	-	-
INTROpost	171 ± 7.89	8.183	<.001*
LABpost	174 ± 7.65	-2.563	.20
SELFpost	172 ± 8.51	-.710	.72

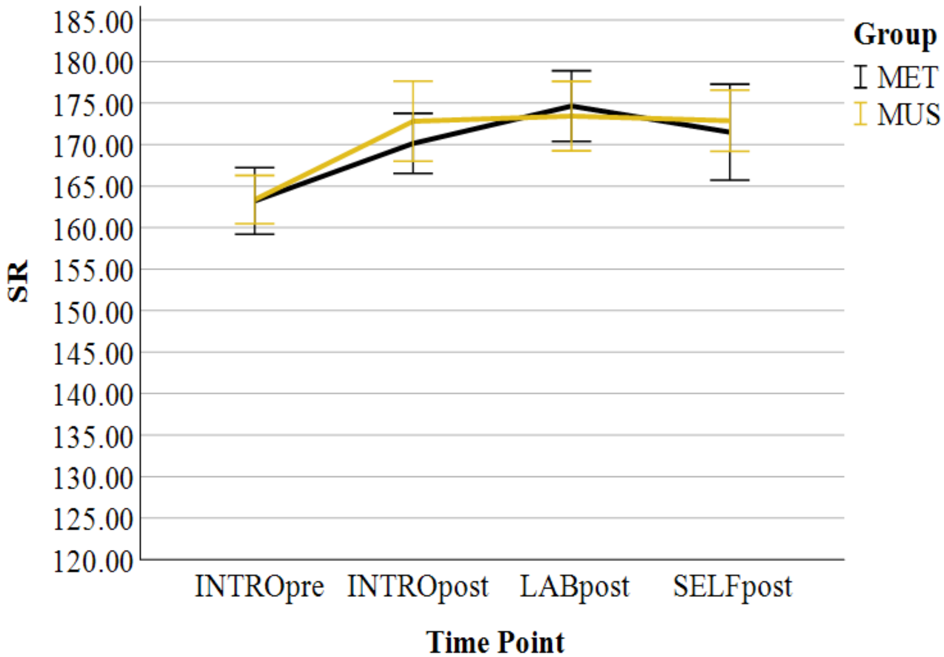
SR= step-rate, spm= steps per minute, SD= standard deviation, INTROpre= introductory pretest, INTROpost= introductory posttest, LABpost= in-lab gait retraining posttest, SELFposttest= self-administered gait retraining posttest, * = significant difference

Table 7. *Percent change in SR by group and timepoint*

Timepoint	Group	SR Percent Δ	Range SR Percent Δ
INTROpost	MET	4.6	0 - 15.5
	MUS	5.5	-1.8 - 14.0
LABpost	MET	7.0	2.4 - 14.6
	MUS	6.2	1.75 - 12.8
SELFpost	MET	5.4	-1.3 - 17.1
	MUS	5.5	1.3 - 9.6

SR= step-rate, INTROpost= introductory posttest, LABpost= In-lab posttest, SELFpost= self-administered posttest, MET= metronome group, MUS= music group, Δ = change, (-) = decrease in SR from preferred.

Figure 10. *Line graph with error bars of SR by group across timepoints.*



Hypothesis 1B (PPA): I hypothesized there would be a significant interaction between group and time where differences in PPA between timepoints depended on group. I expected the MUS group PPA would significantly decrease from the INTROpre to INTROpost and would not significantly change from the INTROpost to LABpost or SELFpost timepoints. I also expected that the MET group PPA would significantly decrease from the INTROpre to INTROpost and would not significantly change from the INTROpost to LABpost but would then increase from the INTROpost to SELFpost.

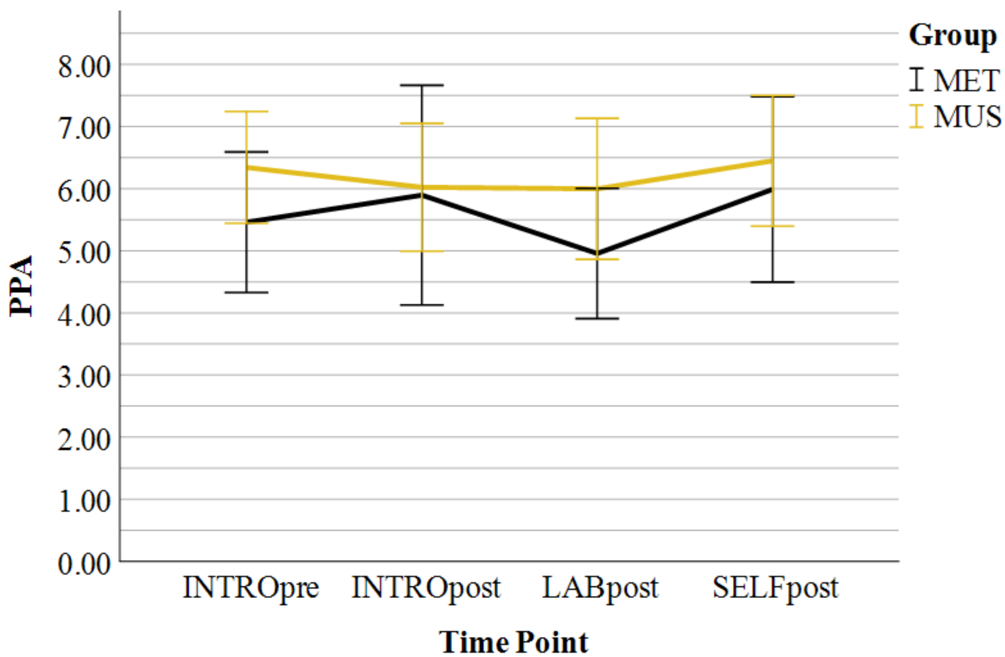
Results 1B (PPA): Results of the 2 X 4 multivariate repeated measures ANOVA indicated no significant interaction ($F_{(9,336)} = .86$, $p = .56$, $n^2_p = .02$) or a main effect of group ($F_{(3,110)} = 1.63$, $p = .19$, $n^2_p = .04$). However, a statistically significant main effect of time was found ($F_{(9,336)} = 4.38$, $p < .001$, $n^2_p = .10$). Follow up tests of pairwise comparisons for timepoints were conducted using a corrected alpha of .0125. Pairwise comparisons did not identify any significant differences between in PPA across timepoints. (Table 8). These results suggest that there were no differences in PPA across timepoints or between groups (Table 8).

Table 8. *PPA by timepoint results*

Timepoint	Mean (gs) ± SD	Mean Difference	p-value
INTROpre	5.90 ± 1.69	-	-
INTROpost	5.96 ± 2.47	.06	.92
LABpost	5.50 ± 2.47	-.48	.40
SELFpost	6.23 ± 2.25	.26	.64

PPA= peak positive tibial acceleration, gs= units of acceleration due to gravity, SD= standard deviation, INTROpre= introductory pretest, INTROpost= introductory posttest, (-) = decrease in PPA, LABpost= in-lab gait retraining posttest, SELFposttest= self-administered gait retraining posttest

Figure 11. *Line graph with error bars of PPA by group across timepoints.*



Hypothesis 1C (Hip Adduction): I hypothesized there would be a significant interaction between group and time where differences in peakHIPADD between timepoints depended on group. I expected the MUS group peakHIPADD would significantly decrease from the INTROpre to INTROpost and but would not significantly change from the INTROpost to LABpost or SELFpost timepoints. It was also expected that the MET group peakHIPADD would significantly decrease from the INTROpre to INTROpost and not significantly change from the INTROpost to LABpost and then would increase from the INTROpost to the SELFpost.

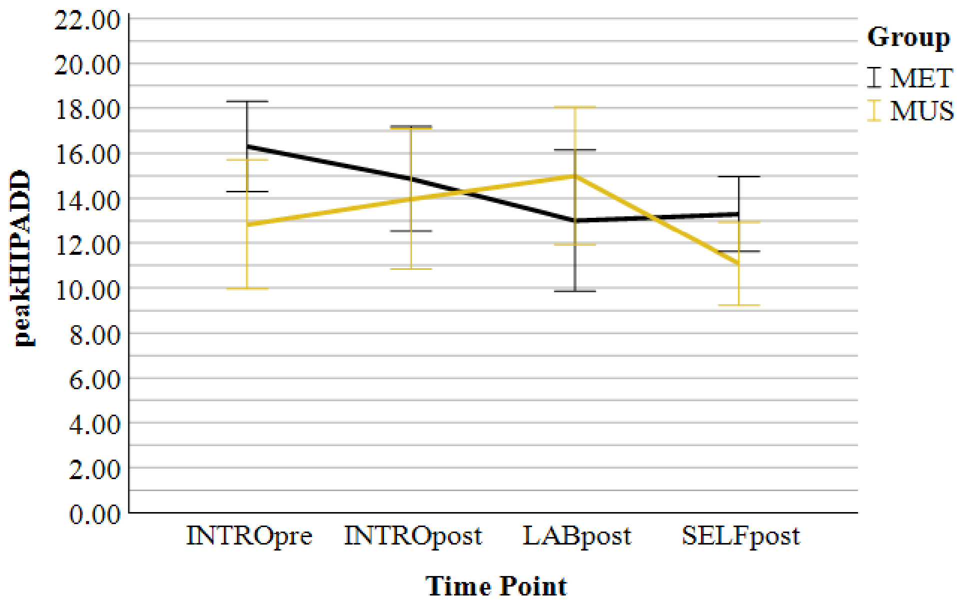
Results 1C (Hip Adduction): Results of the 2 X 4 multivariate repeated measures ANOVA indicated no significant interaction ($F_{(9,336)} = .86$, $p = .56$, $n^2_p = .02$) or a main effect of group ($F_{(3,110)} = 1.63$, $p = .19$, $n^2_p = .04$). However, a statistically significant main effect of time was found ($F_{(9,336)} = 4.38$, $p < .001$, $n^2_p = .10$). Follow up tests of pairwise comparisons for timepoints were conducted using a corrected alpha of .0125. Pairwise comparisons did not identify any significant differences for peakHIPADD across timepoints. (Table 9). These results suggest that there were no differences in peakHIPADD across timepoints or between groups (Table 9).

Table 9. *peakHIPADD by timepoint results*

Timepoint	Mean (°) ± SD	Mean Difference	p-value
INTROpre	14.56 ± 4.85	-	-
INTROpost	14.41 ± 5.03	-.15	.90
LABpost	14.00 ± 5.61	.41	.74
SELFpost	12.19 ± 4.82	-2.26	.07

peakHIPADD= peak stance phase hip adduction, SR= step-rate, ° = degrees, SD= standard deviation, INTROpre= introductory pretest, INTROpost= introductory posttest, (-) = decrease in hip adduction, LABpost= in-lab gait retraining posttest, SELFposttest= self-administered gait retraining posttest

Figure 12. *Line graph with error bars of peakHIPADD by group across timepoints.*



Specific Aim 2:

Specific Aim 2 was to compare differences in RPE change scores across four temporospatial gait retraining sessions between the MUS and MET group.

Specific Aim 2 Hypothesis: It was hypothesized that there would be a main effect of group for RPE change scores, and RPE change scores would be larger and in the positive direction (greater perceived exertion) in the MET group compared to the MUS group, regardless of time point.

Specific Aim 2 Results: Based on the results of the 2 X 4 mixed repeated measures ANOVA, there was not a statistically significant interaction between time and group ($F_{(3, 26)}$ = .59, p = .62, n^2_p = .065), a main effect of time ($F_{(3, 26)}$ = .60, p = .58, n^2_p = .072), or a main effect of group ($F_{(1, 28)}$ = 2.34, p = .14, n^2_p = .08). These results suggest that were no significant differences in RPE change scores between or within the MUS and MET groups, across the four in-lab gait retraining sessions (Table 10).

Table 10. RPE change scores by timepoint results

Timepoint	Mean ± SD	p-value
In-lab session 1	-.37 ± 2.05	.99
In-lab session 2	-.35 ± 2.20	.99
In-lab session 3	-.23 ± 2.23	.99
In-lab session 4	-.63 ± 2.01	.99

RPE= rate of perceived exertion (Borg's scale), SD= standard deviation, (-) = decrease in RPE

Specific Aim 3:

Specific Aim 3 was to determine if there was an association between groups (MUS and MET) and compliance to a self-administered, temporospatial gait retraining protocol and describe the likelihood of compliance between groups. To be categorized as compliant, the participant's monthly average SR had to be within ± 2 spm of the target SR ***AND*** their average running volume had to be at or above the self-reported average running volume.

Specific Aim 3 Hypothesis: It was hypothesized that those in the MUS group would demonstrate a higher likelihood of compliance when compared to those in the MET group.

Specific Aim 3 Results: Two participants of the MET group and 8 participants of the MUS group were compliant to the self-administered gait retraining program. The Fisher's Exact Test indicated a significant association between group and compliance ($p = .05$). An odds ratio was calculated and indicated the MUS group was ~6 times as likely to comply with the self-administered gait retraining program (both maintaining typical running mileage and the assigned target SR) than the MET group (Table 11).

Exploratory analysis of Compliance: To determine what specific element of the compliance definition (SR or miles) was the more common reason for compliance versus noncompliance, the aim 3 analysis was conducted again for only SR and miles criteria of the compliance definition. Ten participants in the MET group and 11 participants of the MUS group were compliant to the assigned target SR during runs in the self-administered gait retraining program. The Fisher's Exact Test indicated a non-significant association between group and compliance to SR alone (p = .60) (Table 13). Two participants in the MET group and 9 participants in the MUS group were compliant to maintaining typical running mileage during the self-administered gait retraining program. Since there were no expected frequencies lower than 5 in this cross tabulation, the Chi-square test was used and indicated a significant association between group and compliance to mileage alone (p = .02). Based on typical running mileage alone, the odds ratio indicated the MUS group was ~7.7 times as likely to comply with the self-administered gait retraining compared to the MET group. All these results suggest the relationship between compliance and group (MET and MUS) may be based on the maintenance of self-reported baseline mileage rather than the maintenance of target SR.

Table 11. *Group by compliance (various criteria) crosstabulation (number of participants)*

Criteria	Group	"compliant"	"noncompliant"
SR and miles	MUS	8	8
	MET	2	12
	Statistical Test	**p-value**	**OR (95% CI)**
	Fisher's Exact Test	.05*	6 (1.30-35.91)
SR only	**Group**	**"compliant"**	**"noncompliant"**
	MUS	11	5
	MET	10	4
	Statistical Test	**p-value**	**OR (95% CI)**
	Fisher's Exact Test	.60	-
Miles	**Group**	**"compliant"**	**"noncompliant"**

	MUS	9	7
	MET	2	12
	Statistical Test	p-value	OR (95% CI)
	Chi-square	.02*	7.71 (1.28-46.36)

SR= step-rate, MET= metronome group, MUS= music group, * = statistically significant

Exploratory Analysis of Time to Acquisition: Data from two individuals within the metronome group was corrupted during the collection process and 4 participants in the MUS group did not meet the target SR consecutively for at least 10 seconds or longer. Therefore, these data were treated as missing and not included in the exploratory analysis. Time to acquisition for the MET group was 16.58 ± 3.37 seconds and was 35.25 ± 12.18 for the MUS group.

The reason the 4 individuals mentioned above that did not meet the time to acquisition criteria were due to the time to acquisition definition including the criteria of 10 seconds or more. When exploring these participants' data on Day 1 or 2 (first or second day of in-lab gait retraining), it was confirmed that they acquired the target SR for 10 consecutive seconds or longer. Prescence of a musical background for these four individuals was also explored for these four individuals, as well. It was revealed two of these four participants did have a musical background of formal dance training and/or playing an instrument and two of these four participants did not report any musical background.

Chapter 5: Discussion

Temporospatial gait retraining is a recommended motor learning intervention clinicians and researchers perform to increase a runner's SR and improve potentially injurious running biomechanics.[28-34] The traditional instruction for temporospatial gait retraining is telling runners to match their footfalls to the beats of a metronome auditory cue.[33-34,36,81,236-238,249,265,267] Since gait retraining is a motor learning intervention, the OPTIMAL theory[38] was used to formulate the methods in this study.

Specific Aim 1:

Prior to this study, there was no evidence in support of other auditory cueing methods, besides the traditional metronome, to increase SR or alter potentially injurious running biomechanics in a temporospatial gait retraining intervention. Specific Aim 1 of this study was to compare SR and running biomechanics of those who used the metronome auditory cueing method (MET group) and a synchronous music auditory cueing method (MUS group) during temporospatial gait retraining. The results partially supported the hypothesis that both auditory cueing methods resulted in an increased SR at the INTROpost and LABpost. Thus, music tempo is effective to create the same alterations in SR as the gold-standard metronome method. Contrary to the hypothesis, however, both groups maintained an increased SR after completing a month of running with the assigned auditory cue without any additional feedback (SELFpost). Also, in contrast to the hypothesis, no significant changes in PPA or peakHIPADD across any time points in either group were found.

Using self-selected, synchronous music to cater to the OPTIMAL theory principles has never been specifically explored prior to the current study. It was posited that the MUS group intervention would produce enhanced expectancies, autonomy, and external focus. Thus, it was thought the MUS group would display "superior" motor performance, defined as a more accurate

(+5%) or consistent display of the target SR over time. When examining each individual runner within the data set, there were instances in which two runners in the MET group decreased their SR at the INTROpost and SELFpost timepoints (Table 14, see "Range SR Percent Δ"). No decreases in SR were found for any runner in the MUS group. Additionally, the MET group seemed to increase their SR slightly more (7%) than the MUS group (~6%) at the LABpost timepoint. It is possible that the MET group intervention did not align as well with OPTIMAL theory principles and caused negative effects during the motor learning process,[38] such as the decreased SR and less accurate SR changes. Still, statistical analysis did not show that the MUS group displayed more accurate or consistent execution of the new SR over time. Therefore, it cannot be concluded that the MUS group had better motor performance and/or motor learning of the new SR when compared to the MET group. The MET group intervention also introduced methods supported by the OPTIMAL theory, such as positive, autonomously phrased language. There may not have been the expected drastic differences between the groups because both groups were receiving motor learning theory-informed practice sessions. Future research can investigate how slight changes in the design of gait retraining protocols impacts motor performance and motor learning for both music and metronome auditory cueing methods.

During posttests, no auditory or verbal cueing was given. Thus, participants perhaps may have relied on memory of the auditory cueing to accurately run at the target SR. Research on the cognitive effects of music theorize music can facilitate long-term memory.[302] Potentially, remembering the tempo of a song was an easier strategy for runners than remembering the tempo of the metronome. Other future research can investigate the how music during motor learning interventions, including but not limited to gait retraining, impacts the cognitive strategies utilized by learners during the process of learning a new skill, as this area of research is relatively scarce.

Few gait retraining studies have investigated the proper "dosage" necessary to acquire and learn gait changes. Dosage of gait retraining may refer to the amount of exposure to instruction or feedback and/or the number of visits needed. Most gait retraining studies have enacted a relatively time-consuming and somewhat arbitrary dosage that may not be realistic at most clinical sites.[86-88,233,234,238,249] Results of this study provide some unique insight into temporospatial gait retraining dosage. The testing times within this study were conducted at times that may reflect the phases of motor learning (acquisition, learning, retention). In the context of this study, acquisition would be accurately reaching the target SR while receiving an auditory cue (music or metronome).[37] In the current study protocol, the learning phase[130] may be marked by maintaining the target SR accurately and consistently with no auditory cueing.[37] Runners may have been advancing through early phases of motor learning after ~5 minutes of auditory cueing demonstrated by a mostly accurate (~+4.6% and ~+5.5%) and consistent (maintained for ~2.5 minutes after cueing removed) increase in SR from the INTROpre to INTROpost. It is theorized that locomotion (gait) is one of the earliest generalized motor programs humans adopt.[37] Individuals can produce variations of the gait generalized motor learning program, such as speed and timing, relatively easily.[37] The flexibility of the gait generalized motor program may explain why runners were able to adjust and possibly begin to learn a new SR so quickly.

The in-lab gait retraining may have helped to reinforce the target SR for runners due to the lack of change between the INTROpost and LABpost. The in-lab gait retraining schedule utilized in this study involved fewer visits and shorter durations of running when compared to other studies.[86-88,233,234,238,249] A commonly cited drawback to current gait retraining protocols is the large amounts of time needed in a research lab environment. Adopting the current study schedule of temporospatial gait retraining may streamline the process in both research studies and clinically. Future research should continue to determine the dosage of all forms of gait retraining. In this study, four sessions of ~15 minutes were used but it is possible that even less than that is needed before runners can acquire and learn a new SR and/or other new gait patterns.

The exploratory analysis of time to acquisition was collected to determine if the increased SR could be acquired similarly for runners regardless of group. No studies have reported data on time to acquisition even for the gold-standard metronome. According to data collected in this study, most runners were able to acquire the target SR for at least 10 seconds within less than a minute after the auditory cueing began. Although, four runners in the music group could not maintain their target SR for 10 consecutive seconds. A potential reason these four individuals could not acquire the change for longer than 10 consecutive seconds was due to musical background. It may seem reasonable that a musical background would result in a better ability to "run to the beats of the music". However, two of the four participants that did not acquire the change reported history of dance training and playing a musical instrument. When combined with previous literature indicating musical background doesn't influence the ability to synchronize movement to music,[59,60] it appears musical background isn't a factor effecting time to acquisition for temporospatial gait retraining. It is important to report that all four individuals were confirmed to have acquired the target SR, according to the operational definition, within the first two sessions of in-lab gait retraining. Although these findings were novel, they may demonstrate that additional time to acquisition may be required with a music auditory cue. Perhaps the musical properties outside of tempo, musicality, and/or rhythm responses that are unique to music auditory cueing but not as prominent in metronome cueing create slightly delayed ability to synchronize running SR as instructed. Since this is the first study to produce this type of data, more research into time to acquisition with music tempo is needed.

The results of the current study contradict that continued use of instruction and/or feedback may disrupt motor learning.[234,238,250,251,252] In contrast to other studies, runners were allowed and encouraged to use their auditory cueing methods for the full duration of every run taken over the self-administered gait retraining phase. The increased SR realized during the INTROpost was retained at the SELFpost for both groups, perhaps indicating it may not be as important to remove auditory cueing overtime as once thought.[234,238,250,251,252] Interestingly, the percent change in SR seemed to be more accurate (closer to the target +5% goal) at the SELFpost when compared to the LABpost (Table 7). With technological advances, individuals can access auditory cueing relatively easily. Potentially, refraining from removing auditory cues may lead to more practice and better retention of new gait. Researchers and clinicians may want to consider more leniency when it comes to continuous use of auditory cueing and faded-feedback schedules.

Importantly, there were no differences in running biomechanics for either auditory cueing method. Positive biomechanical changes are the desired outcome for gait retraining protocols. Still, lack of significant changes for both auditory cueing methods further lends to music being an alternative for the metronome as it appears music did not create different biomechanical outcomes than the metronome. Increasing SR 5% above preferred has led to decreases in vertical loading rate (VLR),[36] a variable representing magnitude of load. Since PPA is a strong correlate to VLR during running,[100-102] it was thought that both groups within the current study would increase SR and thus decrease PPA. Research also has indicated peakHIPADD decreases as SR is increased by 5%,[32] so it was also hypothesized that peakHIPADD would decrease in both groups within this study. As stated though, there were no differences in PPA or peakHIPADD at any of the timepoints in either group. The lack of change in PPA and peakHIPADD is most likely connected to the magnitude of a 5% increase in SR used within this study. More drastic and significant changes in loading variables[30-32,237,266] and peakHIPDD[30,81] seem to be associated with a 7.5-10% increase in SR. Research reports the human ear tends to detect a difference in musical tempo once the original song tempo is increased by ~3-4%.[59] Therefore, selecting only a 5% increase was intentional to potentially avoid runners detecting change in tempo of self-selected songs. Future studies can increase SR by 7.5% and/or 10% using music tempo auditory cueing, which may accompany more drastic decreases in loading variables and peakHIPADD.

In general, the direction of change for PPA for the MUS group did align with the expected outcome. The MET group seemed to experience more sporadic increases in PPA at the LABpost and the SELFpost. Perhaps the compliance to use outside the lab influenced the pattern seen in PPA for the MET group. The changes in peakHIPADD did not necessarily follow the expected change for the MUS group between the INTROpre, INTROpost, and LABpost. However, at the SELFpost, the MUS group did decrease their peakHIPADD by a much larger magnitude than the MET group. The effect sizes for both of these measures were small though, which lends to the thought that the magnitude of change for both measures was perhaps not meaningful. Still, the limited sample size was a potential reason for a lack of significant changes noted in both PPA and peakHIPADD. Future work can increase the sample size using the same protocol and determine if these changes are significant.

There also may not have been significant changes in PPA and peakHIPADD because no instructional cues directed at loading or joint angles were given. In this study, posttest biomechanical data was taken when runners were no longer running with the auditory cueing, like other studies.[30,32,81] The lack of auditory cueing within posttests may have required runners to navigate the increased SR differently than if the auditory cue still playing during the posttest. For example, when the auditory cueing is present, the cognitive process needed to maintain the new SR may decrease.[37] Less cognitive demand could influence movement, such as altered loading and joint angles. Future research may determine if there are differences in kinematics when individuals are running with the auditory cue to facilitate an increase in SR versus when the auditory cue is absent.

PPA and peakHIPADD of participants at the INTROpre were both lower than what is considered "excessive" by previous gait retraining research.[86,235] For that reason, there may not have been significant alterations of PPA and peakHIPADD available to the runners in the current study. Future research may want to screen participants classified as either "high impact runners" or those runners with "excessive" hip adduction to better ensure the desired biomechanical changes can be made. There could have been decreases in VLR,[36] peak impact,[36] braking impulse[32,237] and mechanical energy at the knee and ankle[32] that were not measured in the study. A treadmill was essential to provide instruction and auditory cueing, which did not allow for force data to be collected. The equipment used within this study was also selected specifically because it would be more readily available in most research labs and potentially within clinical sites, as well. Future studies should utilize different biomechanical instrumentation, like an instrumented treadmill that can take force measures, to confirm if decreases in VLR, peak impact, braking impulse, and mechanical energy at the knee and ankle are achieved when a 5% increase in SR is cued using music.

Summary: SR can be altered within a temporospatial gait retraining protocol using either a metronome or music tempo. Clinicians interested in temporospatial gait retraining can offer the choice of either a metronome or music, which may create autonomy and enhance motor learning.[37] It is possible that music can cater to OPTIMAL theory principles and enhance motor performance and motor learning during gait retraining, but the current study measures do not directly support that. Future research should continue to investigate the effect music may have on motor learning interventions. The current study demonstrated that the dosage of in-lab temporospatial gait retraining may be streamlined (less visits and shorter time durations). There were no differences in PPA or peakHIPADD between groups or any of the timepoints likely due to the smaller percentage increase in SR adopted in the current study. Since the results of this study suggest that SR can be altered with music, future research should repeat the study methods using a 7.5-10% increase in SR with hopes to elicit loading changes consistent with a decrease in RRI risk. Research with other biomechanical instrumentation should be conducted to confirm changes in loading can be accomplished with music auditory cues.

Specific Aim 2:

Enhanced expectancies, or positive expectations of upcoming performance on a task during practice of new skills, can facilitate motor learning according to the OPTIMAL theory.[38] Constructs that operationally define enhanced expectancies include improved self-confidence,[39] increased self-efficacy,[40] positive affect (emotions, mood),[41] and decreased perceived exertion.[42] Within this study, an enhanced expectancy was quantified using the Borg's RPE scale.[295] Music has been shown and alleviate perceptions of exertion during exercise[42,54-57] while the metronome auditory cueing method has been shown to *increase* perceptions of exertion during running.[32]

It is largely unknown how gait retraining protocols with the gold standard metronome and/or a music auditory cueing will influence participant expectancies. Therefore, the second aim of this study was to examine how in-lab gait retraining protocols influence perceptions of exertion when the gold-standard metronome and the novel music auditory cueing methods are used. The results of this study did not support the hypothesis that the MUS group would experience less perceived exertion than the MET group across temporospatial gait retraining sessions.

Previous research has reported increased RPE when using a metronome to increase SR[32] so it was thought that increased perceptions of exertion may be found when using the traditional metronome in this study. Overall, both the music and metronome auditory cues neither increase nor decrease perceptions of exertion during a temporospatial gait retraining. However, the insignificant difference provides relevant insight to gait retraining research. In the context of the OPTIMAL theory, the metronome and music did not create the negative expectancy of increased perceptions of exertion. There are known implications of negative expectancies on motor learning and effective practice of new skills.[39,40,159-161] The absence of a negative expectancy (increased perceptions of exertion) is a significant strength of the gait retraining protocol used in this study.

The lack of RPE change between groups contrasted with many other studies within the music and exercise literature.[42,54-57] Several aspects of the study could be responsible for the lower RPE baseline ratings. Significant differences in RPE may not have been found because the average baseline measures of RPE for the participants were ~11 on the RPE scale, which can be considered light-moderate. Gait retraining sessions[86-88,233,234,238,249] typically involve a running duration of up to 30 minutes. The current study only involved running for a 15-minute duration. On average, participants in this study self-reported running about 34.23 ± 14.40 minutes per running session. Perhaps RPE change scores did not change from INTROpre because 15 minutes was a lower running duration than most runners in the study reported maintaining normally.

Since the average RPE at baseline was lower, there was likely little room to decrease RPE measures for these participants. It may be counterproductive to increase the running duration above 15 minutes since results of aim 1 indicate the task goal of increasing SR was accomplished by participants. Further, utilizing a 15-minute duration of running for gait retraining provides the benefits of a less time-intensive intervention. Future research should delve into the expectancies and perceptions of individuals in gait retraining protocols in general. Future research can also begin to determine if the gait retraining schedule itself (duration and number of visits) influences expectancies.

The inclusion criteria in the current study could be an additional aspect that contributed to a lack of differences in RPE across groups and timepoints. Specifically, including all runners, regardless of a preference for running to music, could have influenced the perceptions of exertion during running. Similar studies have found a decrease in perceptions of exertion and did not include individuals based on a preference to exercise to music.[42,54-57] Still, it is certainly possible runners with no preference towards music may not experience significant change in perceptions of exertion regardless of auditory cueing method. Future research could repeat the current study methods except include only those who prefer to run to music, as it is likely those individuals may have unique experiences and perceptions during running without music when compared to those who do not prefer to run to music.[46,47]

Music did not appear to influence perceived exertion within the participants in this study. However, music during exercise can impact many other expectancies and psychological variables[48-52, 55-57,71] that were not measured within this study. Therefore, future research should investigate effects of auditory cueing methods on other expectancies such as enjoyment, motivation, and positive affect.

Summary: Neither the metronome nor synchronous music auditory cueing strategy influenced perception of effort, as measured by RPE, across the timepoints of in-lab gait retraining. There were no studies to investigate the effects of temporospatial gait retraining methods on perceived exertion, prior to this study. Our results suggest that the use of a metronome and music do not create increased perceptions of exertion during the in-lab gait retraining protocol. Therefore, it appears that both a metronome and music can be used as the auditory cueing option without creating the negative expectancy of increased perception of exertion, quantified by the Borg's RPE scale.[295] Ideally, future research should uncover methods that enhance expectancies in some way during gait retraining protocols.

Specific Aim 3

As mentioned, drawbacks of gait retraining interventions include the lack of access to techniques outside of the lab environment and the large time commitment. Researchers started to utilize a self-administrated format of temporospatial gait retraining where the runner practices the new gait on their own, creating minimal time required by the researcher.[30,81] To create permanent change in movement, repetition and practice of the new or altered motor skill (running gait) must take place.[37] Therefore, compliance to practice the gait retraining task goal in a self-administered gait retraining format is of the utmost importance.

Few studies have determined typical compliance levels to self-administered gait retraining protocols or sought out strategies that may increase compliance to self-administered gait retraining. There is no consensus definition on compliance to self-administered gait retraining, therefore, an operational definition for compliance was created for the current study. To be considered compliant runners had to have a monthly average SR within ± 2 spm of the target SR and maintain self-reported average running volume. The results of the analysis supported the hypothesis, as group and compliance were associated, and the MUS group was more likely to comply to the self-administered gait retraining than the MET group.

Results of this study provide the rationale that music auditory cueing may be superior to the traditional metronome auditory cueing. This study is the first to support that gait retraining methods, specifically what type of auditory cueing is used, do have a relationship with compliance to a self-administered gait retraining program. This study is also one of the first to demonstrate music can improve compliance. Those assigned to the MUS group were more compliant with the instruction to practice the new gait than those assigned to the MET group. The OPTIMAL theory references a virtuous cycle in which a learner may continuously seek out practice, perpetuating better motor performance and motor learning of the new skill.[38] Increased compliance of the MUS group, based on running with the new SR and maintaining the typical running mileage, supports music can facilitate the virtuous cycle. A metronome has been identified as a noxious auditory cueing method,[83] which may lead to decreased compliance. Noncompliance is also common when an intervention ignores the psychosocial needs of an individual.[279] Exercisers have showed a preference towards using music in general[180] with the most common activity performed with music being running.[46] Ultimately, if runners are not continually practicing their new gait pattern, motor learning and retention cannot take place. Therefore, researchers and clinicians should consider using music tempo over a metronome for auditory cueing during self-administered gait retraining. Further, running is associated with many health benefits that could improve quality of life.[1] Perhaps future research can use music in hopes of improving compliance to running and physical activity in general.

Results regarding compliance and results of Aim 1 provide further insight on dosage of gait retraining. Interestingly, regardless of the low compliance in the MET group, runners maintained the increased SR at the SELFpost timepoint. It is not yet known how often a runner would have to practice their new gait to be able to retain the changes. It is possible that runners in a self-administered gait retraining intervention do not have to use the auditory cueing method according to the instruction given in this study to retain SR changes. Runners in the current study were told to use the auditory cueing as often as possible during their normal running routine, if not all runs taken. Perhaps the dosage can be lower (e.g., using the auditory cue once a week), and the runner will still retain SR alterations. Studies have used the two-thirds rule,[277,278] that is, compliance to instruction two-thirds of the time, as a meaningful cutoff of dosage to exercise programs. The two-thirds cutoff was based on how often an individual has to comply with the exercise program to experience functional improvements and other health-related benefits.[277,278] More research to develop an evidence-based cut-off point for how often runners need to practice the new gait in a self-administered format is essential, as these cut-off points are currently not available in the literature.

As briefly discussed, it is common in the gait retraining literature to suggest avoiding prolonged exposure to instruction and feedback because it may disrupt motor learning.[28,91,234,250,251] Interestingly, extended exposure and practice with the auditory cueing did not create an inability to retain the new gait at the SELFpost (confirmed by results of specific aim 1). Compliance to only target SR was relatively equal among the group and auditory cueing is easily accessible. Therefore, perhaps researchers and clinicians should not instruct runners to refrain from using auditory cueing during their normal running routines.

Researchers speculate enhanced expectancies and autonomy found during exercising to self-selected music (e.g. improved performance, more efficient motor coordination, and positive feelings) likely lead to increased motivation to practice[38,39,79,80] and increased adherence to the activity.[55] There are a few studies that have tested this theory,[330,304] none of which were conducted in the sport medicine field or strictly on gait retraining. Although enhanced expectancies were not found during the in-lab gait retraining phase, it is possible the music auditory cueing method was more effective during the normal running routines of participants. During the in-lab gait retraining sessions, running duration was much less than runners self-reported. During the self-administered gait retraining phase, runners were partaking in more moderate-hard durations of running. Decreased RPE may have been observed during runs taken during the self-administered gait retraining phase as shown in previous research.[42,52,54-57,179] However, within the current study, expectancies were not measured during the self-administered gait retraining phase, so future research should investigate if improved perceptions of exertion associated with music improve compliance to self-administered gait retraining. The consistently hypothesized mechanism for increased exercise adherence when music is used is through enhanced expectancies.[55-57,71,72] Although all the ways that music can enhance expectancies were not measured in the current study, the assumption that the MUS group may have had enhanced expectancies compared to the MET group is supported heavily within the literature.[47,49,50-52,55-57,62,176,178] Still, future research should continue to explore the relationships and potential underpinning for the preliminary findings relating the use of music auditory cueing and gait retraining compliance.

Investigations of how music can improve adherence may be relevant to the discussion of the current study. It should be briefly noted that compliance is more passive engagement in a prescribed program when compared to adherence.[76,274] Alter et al.[304] reported participants undergoing cardiac rehabilitation identified music as a key factor helping them achieve adherence to desired exercise intensity and duration of exercise. Alter et al.[304] also reported weekly volume of total physical activity was higher among patients using music when compared to those in a non-music group.[304] Further, as time went on, adherence to the exercise program remained strong in those who used music only. [304] It would be an interesting next step to determine if music in gait retraining can influence adherence and to monitor runners for longer periods of time.

Noncompliance was mostly due to the lack of maintenance of average weekly running mileage. Table 11 demonstrates the disparity between groups regarding the compliance criteria. Lower than average running mileage within both groups during the self-administered gait retraining seems to be the driving factor of the relationship between noncompliance and auditory cueing method. In contrast, compliance to the target SR for each group was relatively high, which is aligned with the only other gait retraining study reporting SR adherence during a self-administered gait retraining.[30] Willy et al.[30] indicated that 60% (10/16) of participants were adherent to the increased SR throughout a self-administered phase in which they were not listening to any auditory cue. Compliance to SR during the self-administered phase in the current study was, not surprisingly, higher than 60% for both groups as our participants could hear the auditory cueing on runs. Unfortunately, Willy et al[30] did not measure if runners were still running as often prior to beginning the self-administered gait retraining. How often a runner is practicing their new SR is another important aspect of compliance and adherence, so future research should investigate compliance to both SR accuracy *and* mileage and interventions that may facilitate the compliance.

The MET group (14%) and MUS group (50%) were noncompliant due to not maintaining self-reported average weekly running mileage. The auditory cueing method may only partially explain noncompliance in the groups. Data collection for the current study took place during the winter season in the Milwaukee area, which could have contributed to low compliance with mileage observed in both groups. The exercise environment has been identified as a barrier to exercise adherence.[303] Illness, work- and family-related conflicts, and travel of the participants are likely reasons for noncompliance. There is no reason to suggest any personal factors would be inequal between the groups, but this was not necessarily controlled for in the study methods. Finally, the use of technology runners had not previously been exposed to (WeavRun©) and/or the somewhat limited song bank within the application (for MUS group only) created a barrier to compliance during the self-administered gait retraining phase.[303] For this reason, future research should determine if compliance is improved during certain times of the year, in different areas of the country, and/or when SR retraining is completed using listening platforms runners already engage with during their running routine.

Summary: Runners using the music auditory cueing were more likely to be compliant to the target SR and maintaining their normal mileage than runners assigned the metronome auditory cueing. This is the first study to indicate there is a relationship between compliance to self-administered gait retraining and the method of auditory cueing runners were assigned to use. Runners in both the MUS and MET group could maintain the target SR very well. The disparity in compliance between the groups appeared to be more representative of not maintaining typical running mileage. While the results of specific aims 1 and 2 demonstrated the metronome and music to be interchangeable, specific aim 3 provides a greater rationale to use music to retrain SR within a self-administered gait retraining protocol. The current study was novel in nature and there is limited research to compare the results to, therefore, future research on compliance and strategies to improve compliance to self-administered gait retraining are necessary.

Chapter 6: Conclusions

Introduction

Researchers and clinicians aiming to use temporospatial gait retraining have exclusively instructed SR changes with a metronome auditory cue. Incidental choice and autonomy can be introduced into temporospatial gait retraining if there is evidence demonstrating effectiveness of alternative auditory cueing methods, which can enhance motor learning.[38] Music tempo is measured in beats per minute, similar to a metronome so it may pose a viable alternative to the metronome auditory cueing method.[54,58] Before music can be used as a means to increase SR in temporospatial gait retraining, it was imperative to determine synchronous music also creates the desired changes in SR and running biomechanics essential to prevent and treat RRI. Prior to the current study, there was no comprehensive evidence to indicate positive changes in running biomechanics can be acquired, learned, or retained when using music compared to a metronome in a temporospatial gait retraining protocol. Overall, it seems that the use of music may better account for motor learning theory when compared to a metronome. Music tempo can be better manipulated to create enhanced expectancies,[42,48-57] and autonomy, potentially influencing compliance,[38,39,79,80] and directs attention externally. It was also unknown how temporospatial gait retraining methods influence enhanced expectancies and compliance in any way before this study was conducted.

Specific Aims

Key findings: Music and metronome auditory cueing can be used to illicit increases in SR during the phases of temporospatial gait retraining. There are known implications of negative expectancies on motor learning and effective practice of new skills.[39,40,159-161] Prior to this study, no evidence was available on how the current gold-standard or the novel music auditory cueing method influenced expectations or perceptions of runners. Neither music nor metronome cueing methods and/or the in-lab gait retraining schedule created a negative expectancy of increased perceptions of exertion. Autonomy is an important element to embed into motor learning intervention practice environments.[38] Auditory cueing method was not an area that could be used for incidental choices prior to this study. After confirming music tempo is an alternative method to the metronome, it can be recommended researchers and clinicians pose the choice of auditory cueing method to runners undergoing temporospatial gait retraining.

In-lab gait retraining schedules (dosage) previously adopted for gait retraining protocols have produced desired outcomes[86-88,233,234,238,249] but have not necessarily been examined. Based on some emerging evidence,[253] a much less time-consuming in-lab gait retraining schedule was used for this study. Considering both groups increased their SR and maintained the increased SR throughout the phases of gait retraining, the dosage of the in-lab protocol can be considered effective. Perhaps when conducting a temporospatial gait retraining protocol in a research lab or clinic, the schedule proposed in this study may be favorable compared to the previous 2-week, 8-session in-lab schedule most studies have used.[86-88,233,234,238,249]

As stated, neither auditory cueing set to 5% above preferred running SR led to the desired decreases in PPA and peakHIPADD, or the enhanced expectancy of decreased perceptions of exertion. Ultimately, these findings indicate that adjustments to the current study protocol are in order. The goal of gait retraining interventions is to alter potentially injurious biomechanics. Increasing SR 5% may not be large enough to create positive biomechanical changes. Additionally, the goal of any motor learning intervention should involve producing some sort of enhanced expectancy.[38] There was not an enhanced expectancy of decreased RPE within the current study, potentially due to the auditory cueing methods or the running duration of the in-lab gait retraining sessions. A lack of biomechanical changes and enhanced expectancies indicate even the methods used in the current study, which were designed according to motor learning theory, can be improved upon in future research.

Using a self-administered gait retraining format involves a hands-off and self-guided approach, which is often desired in busy clinical environments. It is important that runners in a self-administered gait retraining comply to practice that is needed to create permanent gait changes. Little evidence on self-administered gait retraining compliance is available. In this study, there was a significant relationship between the method of auditory cueing and the compliance. Overall, music auditory cueing created improved compliance over the metronome auditory cueing. Increased compliance is a significant benefit to using music over the metronome. Researchers and clinicians interested in the self-administered format for temporospatial gait retraining may consider adopting a music auditory cue over the metronome cue based on the current study results.

Limitations:

No study is without limitations. Perhaps the most pertinent limitation within this study lies in the fact that all aspects of the OPTIMAL theory were not directly measured within the current study, namely autonomy, external focus, and goal-action coupling. However, the current study goal was not to test the OPTIMAL theory directly. Rather, the study goal was to introduce a novel auditory cueing method (music) that did not seemingly violate the pillars of the OPTIMAL theory.

There are many ways to measure biomechanical loading and characteristics of motor learning. The current study employed measurement techniques that allowed for more seamless integration of methods into clinical practice. The conclusions made within the study regarding loading were based on PPA values. The inferences made regarding motor learning were based on the observable execution of running SR measured via IMUs. All biomechanical and neuroscientific variables that may capture loading and motor learning were not collected. Furthermore, the variables of interest in this study do not account for all factors that may influence and/or define running biomechanics, motor learning, and enhanced expectancies.

The current study aimed to collect compliance to gait retraining, which does not have a consensus definition within the literature. Therefore, an evidence-based operational definition was derived, and conclusions made regarding compliance are only based on that operational definition. However, as stated, this operational definition was based on recommendations within the literature.[76,276] Compliance data may have been affected by external factors, such as weather, that could not necessarily be controlled in the study design. Another potential barrier to compliance in the current study may have been the use of an additional phone application that was needed for monitoring purposes. Thus, the auditory cueing method may not be the only factor that influenced compliance to the current study gait retraining methods.

No true control group was used in the study design. The use of a control group of runners who did not undergo any type of temporospatial gait retraining may have strengthened the study design and provided more support motor learning, and not Hawthorne effect, was occurring. However, the overarching goal of the current study was to demonstrate music as an alternative to metronome auditory cueing. Therefore, the metronome group can be viewed as the comparative group and satisfied the aims of the current study.

The sample size of the study was relatively small and may impact the statistical results and findings of the study. Additionally, the sample of runners in the study were generally enthused about participating and, therefore, results may not always be generalizable when compared to other groups of less enthused recreational runners. Finally, gait retraining is often completed by those with RRI. However, the participants in this study were healthy, recreational runners. The results of this study may not be generalized to those that have a current RRI.

Areas for Future Research

Overall, this study is the first to examine alternative methods to temporospatial gait retraining so there are various areas for future research that should be explored. In-lab gait retraining is often critiqued due to the time-consuming methods thought to be needed to execute these interventions.[86-88,233,234,238,249] The current study employed a shorter duration in-lab gait retraining schedule (both sessions and minutes) when compared to other studies.[86-88,233,234,238,249] It is possible that much shorter durations are necessary, which can streamline the process of temporospatial gait retraining for runners, researchers, and clinicians. Future research should examine if shorter duration in-lab gait retraining schedules can still produce the desired outcomes. Furthermore, the schedules utilized in self-administered gait retraining have adopted a faded-feedback approach[86-88,233,234,238,249] in which feedback (verbal, visual, auditory, etc.) is gradually faded out and/or participants are told to completely stop using feedback. Within the self-administered phase of this study, participants were not told to gradually discontinue or refrain from their auditory cueing. However, contrary to what previous studies have suggested,[86-88,233,234,238,249] the participants did not experience obvious negative impacts to adopting their new running gait with continuous auditory cueing. Also, technological advances make it relatively easy for runners to continuously access auditory cueing and/or monitor certain aspects of gait on their personal devices. Thus, it can be questioned whether forms of feedback need to be removed. Future research may explore the relationship between retention of new running patterns and faded-feedback gait retraining schedules.

The temporospatial retraining protocol did not yield changes to running biomechanics (PPA and peakHIPADD) regardless of the increased SR runners adopted. The protocol only aimed to increase SR 5%, but this may have been the main reason there were no significant differences found in PPA and peakHIPADD. It is noteworthy that the more novel music condition did not result in differences in running biomechanics when compared to the metronome. To further solidify the effectiveness of music tempo as an alternative to metronome auditory cueing, future research must confirm that music cueing creates the same positive changes to running biomechanics as the metronome when SR is increased in larger increments.

Future gait retraining studies can improve the methods used in this study by screening participants for "faulty" running biomechanics prior to inclusion into the study. The slight changes observed in the study may have been greater if runners were included based on running with high impact or excessive hip adduction. Future studies may also include a true control group in study designs, which can strengthen the speculation of the motor learning process during temporospatial gait retraining.

There were no changes (increases or decreases) in RPE change scores for runners assigned to either auditory cueing methods. While RPE was the operational definition for a potential enhanced expectancy in the current study, there are several other ways enhanced expectancies can be defined and measured. Decreased RPE during exercise was one of the most glaring benefits of music based on the data in the literature.[42,52,54-57,179] However, there are other ways in which music can create a more positive experience for a runner within a gait retraining protocol.[52,55,65] Future research should begin to investigate if other benefits to incorporating music are observed for runners in a gait retraining intervention. Based on the literature,[52] the most logical next steps would be to compare affect and intrinsic motivation between those who perform gait retraining using music versus with a metronome.

To my knowledge, this is the first study to investigate compliance to gait retaining based on auditory cueing method. Therefore, there are several avenues that could be explored regarding compliance to gait retraining in general. First, the current study included all runners, which did not account for the typical preferences participants had in their normal routine. It may be beneficial for future research to determine when posed with a choice of either metronome or music, which is the more common selection for runners undergoing gait retraining. Also, it is important to begin to determine how compliance to gait retraining may be impacted if typical preferences of the runner are aligned with the gait retraining protocol. Finally, a future study can determine if runners are more compliant to gait retraining when using their typical streaming platform instead of an additional, unfamiliar phone application.

The literature regarding music and exercise is large and rich with information. However, there is much less information available on the impact music may have on movement, motor learning, and running biomechanics within the sport medicine field. It is very common within the sport medicine field to aim to alter patients' movement to either optimize performance or prevent injury, which requires both cognitive attention and efficient neurological processing.[37] Music can potentially enhance memory and neurological processing.[61,302] As stated, there are rarely any studies that have explored if music can positively impact interventions aimed to alter movement and biomechanics. Interestingly, synchronizing movement with music may involve different cognitive strategies for patients surrounding their new movement task goals.[61,302] Future research may help uncover potential benefits of music in movement interventions if they exist.

Impact and Significance:

Gait retraining is typically selected as an intervention to re-educate potentially injurious components of gait,[28-30] such as faulty running biomechanics.[30-34] When increasing SR, there have been decreases in VLR,[36] peak impact,[36] braking impulse[32,237] and mechanical energy at the knee and ankle[32] reported. With these decreases in loading, come decreases in RRI risk.[18,19,22,92,97,103] Therefore, temporospatial gait retraining has significant potential to impact the sport medicine community positively. However, one evidence-based method does not provide sufficient options for temporospatial gait retraining interventions that work for clinicians in various settings. It is imperative to continue to provide evidence in favor of multiple, effective strategies for temporospatial gait retraining. The main aim of this study was to provide some foundation and rationale for diversifying gait retraining auditory cueing methods. Clinicians, researchers, and/or runners interested in using a temporospatial gait retraining now have a choice of either a music or metronome auditory cueing methods, which may create autonomy and enhance motor learning.[37]

Temporospatial gait retraining may be streamlined if researchers and clinicians choose to adopt the less time-demanding schedule used in this study that led to the desired alterations of SR. The technology for the intervention (free cell phone application) was intentionally selected to encourage more seamless integration into many clinical settings. The current study results help practitioners in the sport medicine community enhance patient care by accounting for patient wants and needs when they want to pursue temporospatial gait retraining. Many clinicians and clinical facilities may struggle to produce the equipment and time needed for temporospatial gait retraining, but this study offers a solution to both of those drawbacks.

There are few studies to ground gait retraining intervention designs within a theory of motor learning, which may leave researchers to question whether the already successful outcomes of gait retraining can be further improved. The OPTIMAL theory[38] was used to develop and guide the methods of the current study. Within any sport medicine intervention aimed to alter movement in some capacity, inclusion of OPTIMAL theory principles is a superior approach.[44,45] The gait retraining methods shown to be effective in the current study can be used as a guideline for future gait retraining studies aiming to be mindful of motor learning theory in research designs. The OPTIMAL theory[38] also posits that both physical and psychosocial variables impact the outcomes of motor learning intervention. Designing the current study according to the OPTIMAL theory[38] acknowledged and better accounted for the psychosocial aspects of learning new gait changes. There is very little known regarding the psychological and social impact gait retraining has for runners, but these impacts may very well influence outcomes.[38] Therefore, a holistic outlook on the gait retraining intervention is in order.

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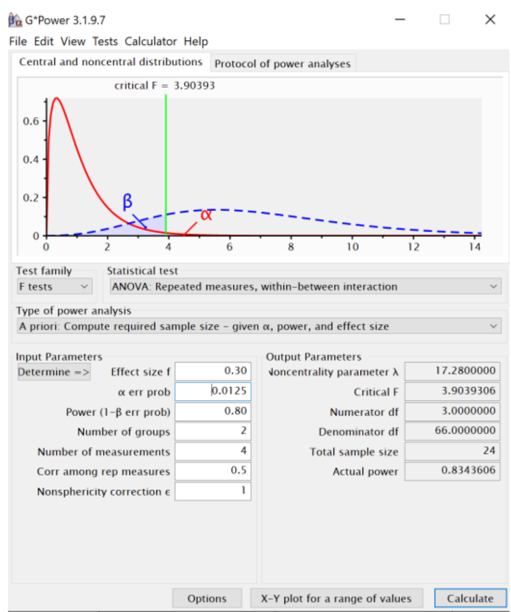
Appendices

Appendix A: Power Analysis and Sample Size Justification

As shown in the table, I used the published data of several studies and their effect sizes to determine what would be best for my study. I used the lowest effect size I found within the pertinent published data (music and metronome comparisons of RPE = .30) to inform my decision to recruit at least 24 participants total as highlighted in the picture above. When I adjusted the p-value to .025 (the adjusted alpha needed to account for simple main effects of group), the sample size required was 20. When I adjusted the p-value to .0125 (the adjusted alpha needed to account for simple main effects of time), the sample size required increased to 24. In order to account for at least a 10% drop out rate, which is consistent with the gait retraining studies as listed in the table below, I would have to recruit 27 participants. I aimed to recruit 30 participants (15 in each group) for even groups, and this also aligned well with the number of participants per group recruited in the largest temporospatial gait retraining study to date (Futrell et al.). A screenshot of the power analysis screen is included below. A table of similar gait retraining studies and their power analysis results, how many participants were included in the study, and the dropout rate for each is also included below.

Study	**Variable of Interest**	**Effect sizes from study used for power calculation**	**Sample size needed for MY study according to G*power**
Futrell et al.	Loading rate	.50	8
Bramah et al.	Peak hip adduction joint angle	.43	10
Neal et al.	Peak hip adduction joint angle	.54	8
Wang et al.	SR	.86	4
Willy et al.	Peak hip adduction	.61	6
Bood et al.	RPE	.30	24



Study	Sample needed for this study based on their own power analysis	Sample Collected	Comparisons this study made	Drop out
Futrell et al.	2 groups of 14 participants = 28 participants	36 participants	2 X 4 RM ANOVA comparing 2 groups over 4 time points	3 (8%)
Bramah et al.	12 participants, no groups	12 participants	3 timepoints RM ANOVA	2 (16%)
Neal et al.	10 participants, no groups	10 participants	Cohen's d and mean differences with 95% CI from baseline to post retraining time points	1 (10%)
Wang et al.	2 groups of 13 = 26 participants	24 participants	2 X 2 RM ANOVA comparing 2 groups over 2 time points	2 (8%)
Willy et al.	2 groups of 13= 26 participants	30 participants	Separate 2 X 3 RM ANOVA comparing 2 groups over 3 time points	1 (3%)
Bood et al.	16 participants	19 participants	2 X 3 RM ANOVA comparing 2 groups over 3 time points	Not indicated

Appendix B: Recruitment Materials
VERBAL ANNOUNCMENT TEXT (This will be read aloud)

My name is Erin Lally, and I am a doctoral student at University of Wisconsin-Milwaukee in the Integrated Movement Science and Athletic Training lab. I am looking for participants to volunteer for my study The title of the study is "Using Music to Modify Step-rate and Running Biomechanics in Healthy Runners".

I want to investigate if using music to retrain running step rate results in greater improvements in hip and knee angles, leg loading, perceived exertion, and compliance.

Participation in this research is completely voluntary. If you agree to participate, you can always change your mind later. There are no negative consequences in whatever you decide. This study has been approved by the University of Wisconsin-Milwaukee Institutional Review Board (______) (1).

You are eligible to participate in this study if you meet the following criteria:

- Men & Women, ages 18 to 50 who:
  1. Have no injury(ies) restricting their ability to run
  2. Have no history of medical condition that impairs balance or current diagnosis of a condition that may impair balance (concussion, neurological impairments, etc.)
  3. Are not currently pregnant
  4. Do not have an implanted pacemaker
  5. Maintain at least approximately 8km or 5 miles of running distance
  6. Have access to an iPhone or iPod to run with
  7. Use a rearfoot strike while running (which I will screen for)
  8. Run with a step-rate of less than 170 steps per minute (which I will screen for)

During the study there are several activities that you will complete:?

- 4 movement analysis testing while running (~85 minutes over a month period)
- 4 gait retraining sessions (~60 minutes over a week)
- Self-gait retraining session during your normal running routine for a one month period
- Download the Weav Run application
- **Possible benefits**
- Some participants may benefit from the gait retraining intervention and enjoy the Weav Run application used in this study for free for the duration of the study.
- Similar studies have indicated a decreased risk of running related injury from interventions like the one used in this study.

Compensation

- Free universal arm band for your phone while exercising
- $50.00 gift card
- Free access to Weav Run application for the duration of the study.

Please write your name and contact information down on the sheet I am circulating. If you would like to schedule a phone screening session to learn more about volunteering.

EMAIL ANNOUNCEMENT

My name is Erin Lally, and I am a doctoral student at University of Wisconsin-Milwaukee in the Integrated Movement Science and Athletic Training lab. I am looking for participants to volunteer for my study. The title of the study is "Using Music to Modify Step-rate and Running Biomechanics in Healthy Runners".

I want to investigate if using music to retrain running step rate results in greater improvements in hip and knee angles, leg loading, perceived exertion, and compliance.

Participation in this research is completely voluntary. If you agree to participate, you can always change your mind later. There are no negative consequences in whatever you decide. This study has been approved by the University of Wisconsin-Milwaukee Institutional Review Board (______) (1).

You are eligible to participate in this study if you meet the following criteria:

- Men & Women, ages 18 to 50 who:
    1. Have no injury(ies) restricting their ability to run
    2. Have no history of medical condition that impairs balance or current diagnosis of a condition that may impair balance (concussion, neurological impairments, etc.)
    3. Are not currently pregnant
    4. Do not have an implanted pacemaker
    5. Maintain at least approximately 8km or 5 miles of running distance
    6. Have access to an iPhone or iPod to run with
    7. Use a rearfoot strike while running (which I will screen for)
    8. Run with a step-rate of less than 170 steps per minute (which I will screen for)

During the study there are several activities that you will complete:?

- 4 movement analysis testing while running (~85 minutes over a month period)
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Compensation

- Free universal arm band for your phone while exercising
- $50.00 gift card

- Free access to Weav Run application for the duration of the study.

Please email me if you would like to schedule a phone screening session to learn more about volunteering.

Thanks,

Erin

SOCIAL MEDIA TEXT

Do you run for the fun of it and use an iPhone? Are you interested in techniques that may improve your running performance and help prevent injury? Would you like to participate in a research study on running gait retraining? The Integrated Movement Science and Athletic Training Laboratory at University of Wisconsin-Milwaukee is conducting a research study on gait retraining in runners. You will receive free access to a fitness phone application, free arm band to hold your phone during exercise, and a $50.00 gift card when you complete this study. Email emlally@uwm.edu, or message me (personal message or email address) for more information

Do you regularly run and have an iPhone?
Want to participate in research on running gait retraining?

What is the purpose of this study?

I want to investigate if using music to retrain running step rate results in greater improvements in hip and knee angles, leg loading, perceived exertion, and compliance.

Who Can Participate?

- Men & Women, ages 18 to 50 who
    1. Have no injury restricting their ability to run
    2. Have no history of medical condition that impairs balance or current diagnosis of a condition that may impair balance (concussion, neurological impairments, etc.)
    3. Are not currently pregnant
    4. Do not have an implanted pacemaker
    5. Maintain at least approximately 8km of average weekly running mileage
    6. Have access to an iPhone or iPod to run with
    7. Use a rearfoot strike (which I will screen for)
    8. Run with a step-rate of less than 170 steps per minute (which I will screen for)

What Would I Have to Do?

- 4 movement analysis testing while running (~85 minutes over a month period)
- 4 gait retraining sessions (~60 minutes over a week)
- Self-gait retraining session during your normal running routine for a one month period
- Download the Weav Run application (if you have an iPhone).

You will receive a running biomechanical analysis & running gait retraining that may decrease injury and boost running performance!

+

a FREE running arm band for exercising, FREE access to a running fitness phone application, & 50$ Gift Card when the study is complete!

In case of any questions or to volunteer, please contact: **Erin Lally (708)-259-4138**

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Erin Lally

Appendix C: Screening Form

PHONE SCREENING FORM

(To be read by research assistant) To make sure that you are eligible for this study, I need to ask you several questions about your running habits and health history. Is this okay with you? Please listen carefully and answer to the best of your ability. If you don't understand a question please ask. This information will not be recorded or used for research purposes unless you are eligible, and consent to be in the study.

INCLUSION CRITERIA: (all responses should be "yes")

Rearfoot strike pattern?	Yes No
Age 18-50 years?	Yes No
Do you maintain an average of 5 miles of running training per week?	Yes No
Do you have access to an iPhone or iPod for regular use?	Yes No
When you are running, do you have a rearfoot strike (e.g. your heel hits the ground first during a step)?	Yes No Unsure (OK proceed to in person screening)

EXCLUSION CRITERIA: (all responses should be "no")

Do you have a history of medical condition that compromises your balance (i.e. concussion, neurological impairments, etc.)	Yes No
Are you or could you be pregnant?	Yes No
Do you have an implanted pacemaker?	Yes No
Are you currently free of injury (of any kind) restricting your running participation?	Yes No
SR greater than 170spm?	Yes No

1. **Screening Failures (NO for any inclusion criteria, and YES for any exclusion criteria)**

I am sorry to inform you that you do not qualify for our study. We thank you for your time and interest in this study. Do you have any further questions?

2. **Screening Successes (YES for any inclusion criteria, and NO for any exclusion criteria)**

I am pleased to inform you that you may qualify for our study. If you are still interested in participating, we will now need to schedule you for an initial testing session. This session will take approximately 1 hour. All of the procedures of this study are outlined in the consent form that you can review before you agree to be in the study. Would you like me to e-mail you a copy of it?

If "Yes", record e-mail address here: ____

If "No", proceed to next section.

Schedule for Initial Testing:

Date: _________________ Time: ____________ AM / PM

Do you have any other questions about the study?

Explain the directions to campus.

Explain what clothes to wear.

Appendix D: Consent Form

Study title	Using Music to Modify Step-rate and Running Biomechanics in Healthy Runners
Researcher[s]	Erin Lally, MS, ATC (student in the PhD Health Sciences program); Jennifer Earl-Boehm PhD, ATC; Hayley Ericksen, PhD, ATC; Madison Mach, MS

We're inviting you to participate in a study. Participation is completely voluntary. If you agree to participate now, you can always change your mind later. There are no negative consequences, whatever you decide.

Overview

Purpose: We want to investigate if using music to retrain running step rate results in greater improvements in hip and knee angles, leg loading, perceived exertion, and compliance.

Procedures: You will be asked to complete several sessions of running while listening to an auditory cue and having your body movements recorded in a biomechanics lab. You will also be asked to use the auditory cue for your normal running routine for 4 weeks.

Time Commitment: You will complete 2 sessions that will take ~45 minutes and 6 sessions that will take ~25 minutes.

Primary risks: You may experience some muscle soreness as a result of testing and training your new running form. Falling during treadmill running is an unlikely risk, but possible.

Benefits: Some participants may benefit from the given gait retraining intervention by improved running form and less impact on the legs. It is anticipated that the study will provide evidence if music can be effectively used to increase step rate for runners, which may lead to an alternative strategy to use when gait retraining.

What will I do?

Location and time	What will I do?

First testing session:
Time: 45 minutes
 	
Location: University of Wisconsin Milwaukee Campus
 	
Musculoskeletal Injury Biomechanics Laboratory (MIBL) (Enderis Hall 132)
 	
Or
	• Before you arrive:
	  ○ We ask you wear tight fitting shorts and a tank top or t-shirt and shoes you will run in for the duration of the study.
	• When you arrive, we will confirm eligibility and obtain consent for the study: (~5 minutes) by doing the following:
	  ○ Reviewing the consent form with the researcher and signing.
	  ○ Complete a demographic form including age, height and weight, etc.
	  ○ Assigned participant ID code under which all of your data will be saved.
	  ○ You will be randomly placed into one of two intervention groups.

Pavilion 356	• Perform a pretest (~20 minutes) consisting of the following:
	  ○ Download the Weav Run application onto your phone. You will either be asked to create a playlist you would like to run to consisting of ~10 minutes of music or be introduced to the metronome track you will be using via the app.
	  ○ Sensors to measure motion of your joints and impact experienced during running will be placed on your upper thigh, lower leg, and foot with Velcro straps.
	  ○ Jog on a treadmill at your own comfortable pace for 5-minutes while running form and step-rate data are collected. The researcher will then calculate your target step-rate.
	• You will then complete the intervention consisting of the following: (~10 mins)
	  ○ Placing an armband on your upper arm
	  ○ Turning the volume of the auditory cue up while set to target step-rate.
	  ○ Running while matching your foot strikes to the audio cue (music or metronome)
	  ○ The researcher will also provide feedback for 5 minutes while you continue running for 5 minutes using the audio cue at the target step-rate. You will continue running for 5 more minutes while the researcher collects your running form and step-rate again.

Retraining Sessions:
Time: ~25 minutes
Location: Same as above
	• Includes 4 sessions of running retraining supervised by study personnel over, starting 48-72 hours after the first testing session
	• You may wear your own athletic clothes and the shoes that you ran in on the first day of testing.
	• You will be asked to run on treadmill at your preferred speed for 15 minutes with the same instructions/ audio cue (MET or MUS) used the first testing session.
	• Instruction from the researcher and the audio cue will be gradually removed each session according to the following schedule
	  ○ Day 1: 15 mins of running, 15 minutes of feedback
	  ○ Day 2: 15 mins of running, ~11 minutes of feedback
	  ○ Day 3: 15 mins of running, ~7 minutes of feedback
	  ○ Day 4: 15 mins of running, ~4 minutes of feedback
	• We will ask you about your perceived exertion at the end of every session

Post-retraining testing session:
 	
Time: ~25 minutes
Location: Same as above
	• Before you arrive:
	  ○ You will be asked to wear tight fitting shorts and a tank top or t-shirt and shoes you wore on the first day of testing.
	• After you arrive:
	  ○ Sensors to measure motion of your joints and impact experienced during running will be placed on your upper thigh, lower leg, and foot with Velcro straps.

	○ Jog on a treadmill at your own comfortable pace for 5-minutes while running form and step-rate data are collected. The researcher will then calculate your target step-rate.
Self-administered gait retraining sessions: When/where participants choose to run	• You will maintain the new gait pattern while independently using the Weav Run app during your normal running routine and I will send an email remining you to export data, including detected running step-rate, time spent running, and target step-rate, directly from the Weav Run application to a survey upload. • You will also be asked to wear two Rubscribe footpods on your shoelaces while you run so we can collect 3D biomechanical data during the self-administration phase. • You will schedule your one-month post testing session within 72 hours of your 30th day of self-administered gait retraining.
One-month post-testing session: Time: ~25 minutes Location: Same as above	• Before you arrive: ○ You will be asked to wear tight fitting shorts and a tank top or t-shirt and shoes you wore on the first day of testing. • After you arrive: ○ Sensors to measure motion of your joints and impact experienced during running will be placed on your upper thigh, lower leg, and foot with Velcro straps. ○ Jog on a treadmill at your own comfortable pace for 5-minutes while running form and step-rate data are collected. The researcher will then calculate your target step-rate.

Risks

Possible risks	How we're minimizing these risks
Breach of confidentiality (your data being seen by someone who shouldn't have access to it)	• All identifying information is removed and replaced with a study ID. • When data collection is completed, the code will be destroyed. • We'll store all electronic data on a password-protected, encrypted computer. • We'll store all paper data in a locked filing cabinet in a locked office. • While the study is still active, we'll keep your identifying information separate from your research data, but we'll be able to link it to you by using a study ID. We will destroy this link after we finish collecting and analyzing the data.
• Muscle soreness as a result of testing and training. • Falling during treadmill running (unlikely)	• You will be allowed to practice all tests and do warming up exercise prior to data collection until you feel comfortable. You will not be performing an excessive amount of running outside of your normal training habits. If you feel any soreness, sudden increase of symptoms or development of new symptoms while participating in this study, please tell the investigators as soon as possible. • You will be allowed to practice running on the treadmill until you are comfortable. • If you are injured during the study all study personnel are trained in CPR and first aid. If you need additional care, you may seek additional care from the Norris Health Center of another provider at your own expense.

Other Study Information

Possible benefits	• Some participants may benefit from the given gait retraining intervention by improved running form and less impact on the legs. Participants may also enjoy the access to the phone application used in this study. • It is anticipated that the study will provide evidence on the if music can be effectively used to increase step rate for runners, which may lead to an alternative strategy to use when gait retraining.
Estimated number of participants	32 participants
How long will it take?	~185 minutes over the time span of 1 month
Costs	You'll pay for your own transportation and parking. There are no costs related to the Weav Run Application, however, you will have to agree to the terms and services of using this application.
Compensation	You will receive free access to Weav Run for the duration of the study. You will keep your universal arm band to secure your phone when exercising. You will receive a $50 gift card after the completion of the study. Due to UWM policy and IRS regulations, we may have to collect your name, address, social security/ tax ID number, and signature to give you this compensation.
Results of the Study.	Results of the study can be reviewed with the participant by the PI via in person meeting due to the complex nature of the data and the equipment being used to collect the data. However, the PI will explain the complex biomechanical data in layman's terms to the participant if they request.
Future research	De-identified (all identifying information removed) data may be shared with other researchers and may be used for further analysis of the data. You won't be told specific details about these future research studies
Removal from the study	If ineligible for the study upon the first visit, your data will be destroyed, and you will be removed from the study. Any participants fail to follow the study request will be removed from the study. This includes failure to complete the movement analysis testing after gait retraining in the lab or after the self-administration phase. You will also not be compensated unless you complete the self-administration phase by exporting your data or indicating you do not have any data to export. Sudden development of any new conditions that could prevent them from running will lead to discontinuing the trials. Any change in inclusion/exclusion criteria noted throughout the study may result in removal from the study.
Funding source	The Wisconsin Athletic Trainers' Association and the Great Lakes Athletic Trainers' Association is funding this research study.

What if I am harmed because I was in this study?

If you're harmed from being in this study, let us know. If it's an emergency, get help from 911 or your doctor right away and tell us afterward. We can help you find resources if you need psychological help. You or your insurance will have to pay for all costs of any treatment you need.

Confidentiality and Data Security

We'll collect the following identifying information for the research: Signature on Consent Form. We'll also collect your name, email address, and phone number. This information is necessary so that we can contact you to schedule sessions in the lab. This information is necessary to allow us to perform the study and have evidence that you agreed to all of the risks, benefits, knowledge of the study, and participation of the study. We will keep a copy of your signed consent form and you will receive a copy of the full consent form with signatures for your referral of the study and contact information if you have any questions after the study is performed.

Where will data be stored?	Electronic data will be stored on a laboratory dedicated computer or server that are protected by password access only. The Weav Run data exports will be downloaded from the Qualtrics survey (Excel) and coded according to your participant ID and stored on a laboratory dedicated computer or server that are protected by password access only. Other personal information will be kept in a locked cabinet in a locked office.
How long will it be kept?	Identifiable data will be deleted upon the completion of active data collection of the study. All other data, with your participant codes will be kept indefinitely

Who can see my data?	**Why?**	**Type of data**
The researchers	To analyze the data and conduct the study	Each participant's data will be given a unique ID (letter and number) that will be linked to their name during the active phases of data collection, in case they need to be contacted. However, the participant ID (not be linked with the participant's name) will be used for all data reviewing, reducing, and analyzing. After active data collection, all your data will be deidentified. The 3D motion capture electronic data will be saved by participant's ID code from the data sheet. Electronic data will be stored on a laboratory dedicated computer or server that are protected by password access only.
The IRB (Institutional Review Board) at UWM The Office for Human Research Protections (OHRP) or other federal agencies	To ensure we're following laws and ethical guidelines	All participants' information on the "Data collection form" will be given an ID code (letter and number) that is uniquely associated with each individual part. The ID code and informed consent with the participant's name and email will be stored in a separate locked office in a locked filing cabinet. The 3D motion capture electronic data will be saved by participant's ID code from the data sheet. Electronic data will be stored on a laboratory dedicated computer or server that are protected by password access only.

Anyone (public)	If we share our findings in publications or presentations Our funding agency requires us to make our dataset public so other researchers can use it.	De-identified data may be used in future research. We may also decide to present what we find to others or publish our results in scientific journals or at scientific conferences. Information that identifies you personally will not be released without your written permission.

Contact information:

For questions about the research	Erin Lally, MS, ATC	emlally@uwm.edu
For questions about your rights as a research participant	IRB (Institutional Review Board; provides ethics oversight)	414-662-3544/ irbinfo@uwm.edu
For complaints or problems	Jennifer Earl-Boehm, PhD, ATC	414-229-3227 / jearl@uwm.edu
	IRB	414-662-3544/ irbinfo@uwm.edu

Signatures

If you have had all your questions answered and would like to participate in this study, sign on the lines below. Remember, your participation is completely voluntary, and you're free to withdraw from the study at any time.

____

Name of Participant (print)

____ __________

Signature of Participant Date

____

Name of Researcher obtaining consent (print)

____ __________

Signature of Researcher obtaining consent Dat

Appendix E: Data Collection Form

DATA COLLECTION FORM

Participant code: S_______ **Date :_________**

Inclusion/exclusion criteria confirmed: Yes, criteria met

Age: _____ **Ht: ______**cm **Wt: ______**kg

What is your gender identity?:

- ☐ Man
- ☐ Women
- ☐ Another gender identity not listed here

What is/was your sex assigned at birth?:

- ☐ Male
- ☐ Female

What is your race?:

- ☐ Black or African American
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Native Hawaiian or Other Pacific Islander
- ☐ Hispanic or Latina/o
- ☐ Multiracial
- ☐ White

Which is your dominant limb (limb used to kick a ball)? Right______ Left_______

Do you have a musical background (e.g., dance, playing an instrument, or counting music):

Yes No

Average running mileage per week: ______________

Average running frequency (sessions) per week: ______________

Average running duration (time) per week: ______________

Group allocation: MET MUS

Preferred SR:_______(exclude if > 170 steps per minute) **Preferred speed: _________**

Target Step Rate (5% above step rate) ______________

Acquisition Testing Time:

Trial	**Completed**	**Data Reviewed and Exported**
T1 Pretest	☐	
Introductory Session	☐ ☐ ☐	
T2 Posttest	☐	

Gait Retraining Testing Time:

Session	**Run time**	**Feedback time**	**RPE at conclusion**	**Speed**	**Complete**
1 Date:	15 mins	15 mins			☐
2 Date:	15 mins	11 mins			☐
3 Date:	15 mins	7 mins			☐
4 Date:	15 mins	4 mins			☐
T3 Posttest	☐	None			☐

One-month Testing Time:

Trial	**Completed**	**Data Reviewed and Exported**
T4 Posttest Date:	☐ ☐ ☐	

☐ All Weav Run Data Exported

☐ Gift card awarded

☐ All equipment returned (if applicable)

Appendix F: Weav Run Guide Music Group

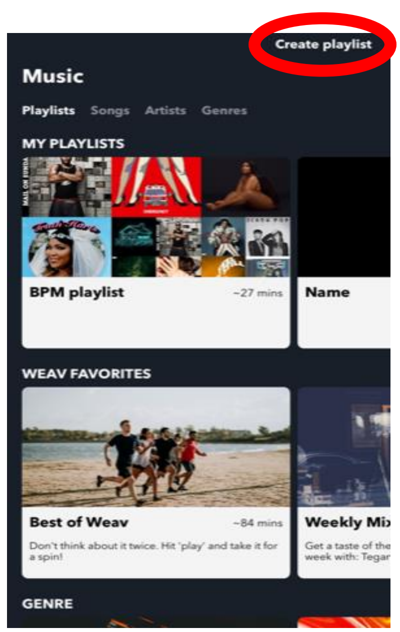
For your first day of testing, please follow the below instructions up to bullet point "h.". You will have free access to the Weav Run application using the link for the duration of the study.

1. **Download the Weav Run application using the following link:**
   - **https://weav.app.link/gait-retraining-study-uwm**
   - **OR scan the QR code**
   - **The icon looks like this →**

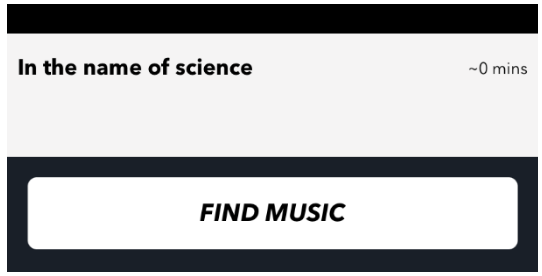
1. **Create an account**

2. **Create a playlist**
   - **a.** Select songs that you would enjoy running to and that put you in the headspace to run. Typically, upbeat songs provide the best experiences for physical activity. However, select whatever you feel you would enjoy working out to.
   - **b.** Do this by going to the bottom bar of the app screen and selecting the "Music" tab

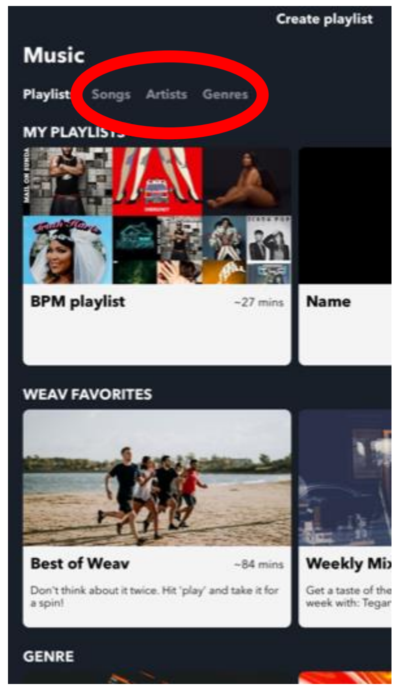
   - **c. You will then see a page that looks like the picture below. Click on "Create playlist" in the upper right-hand corner of the screen.**



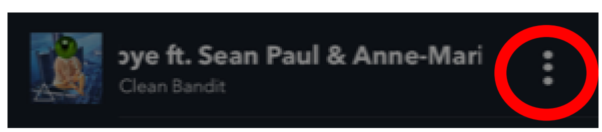
d. Name your playlist whatever you want. I named mine "In the Name of Science" Once you see this screen, click "Find Music".



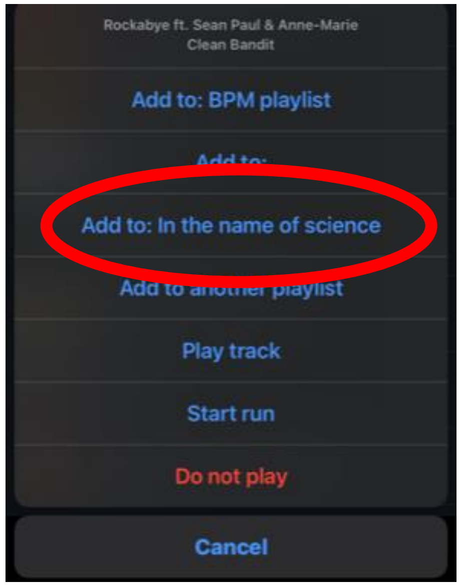
e. You will be taken back to the screen pictured below. Click on "Songs", "Albums", or "Genres" to begin adding music.



f. When you want to add a song to your running playlist, click on the three dots to the right of the song title.



g. Options will come up like the screen below. Select that you want to add this song to your running playlist created for this study. Again, mine was named "In the name of science" so I added it to that playlist.



h. **Continue to add songs to your playlist until you have approximately 30 mins of music.**

3. **Complete your run with your Weav Run Application**
   a. **When finished, name your run with the following criteria.**
      i. **ParticipantID_group_intervention**

4. **Before you leave today, go to the settings tab.**

   a. **Hit "Help and Feedback"**
      i. **In the text box, type the following.**
      ii. **You can also use the "Scan Text" feature on your iPhone by holding down the cursor while in the text box.**

I am a participant in the UWM gait retraining study. I will need access to the playlists and the Export feature for this study. Thanks!

5. When you have access, go to the "sessions" tab at the bottom.

Click on the run you completed today and export to mail.

i. Send to: emlally@uwm.edu
ii. Subject Line: Intervention Trial Running Data

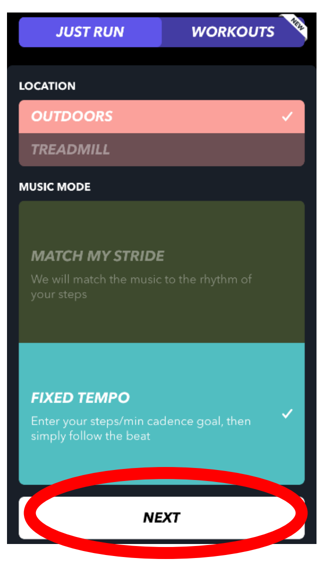
For this second and third phases of this study, you will be asked to continue your normal running volume (miles, frequency and/or duration) throughout the next month. We ask that you use the Weav Run App every time you run throughout the gait retraining study. Directions are described below. You can run on a treadmill, indoors on a track, or outdoors. Please only use the playlists you have used in the lab until told otherwise.

Before you start running:

6. Access your playlist to start running.

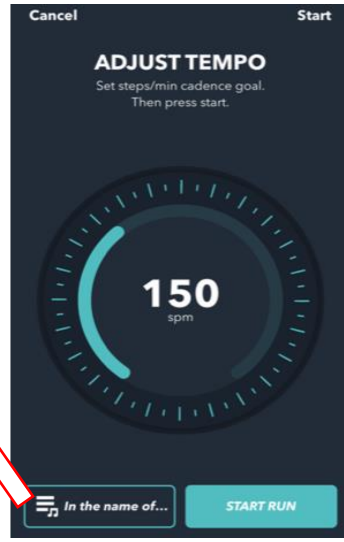
a. Do this by going to the bottom bar of the app screen and selecting the "Run" tab.

7. Before you begin to run, open the Weav Run App. You should see the screen below. If not, make sure you have "Just Run" selected. Select "Treadmill" or "Outdoor" accordingly and "Fixed Tempo". Then click "Next".



8. Don't start running just yet!

Make sure this has the name of the playlist you built. If not, click this button and select the playlist you built.



Make sure this number is set to your target step-rate given to you.

9. **Hit Start run and then slide or hit the arrow down to get back to the main page shown below and go!**

<u>Ending your run:</u>

10. **Complete your run with your Weav Run Application**
    a. **When finished, name your run with the following criteria.**
        i. **ParticipantID_group_intervention**

11. **Before you leave today, go to the settings tab.**

12. When you have access, go to the “sessions” tab at the bottom.

Click on the run you completed today and export to mail.

i. Send to: emlally@uwm.edu
ii. Subject Line: Running Data Participant ID

Appendix G: Weav Run Guide Metronome Group

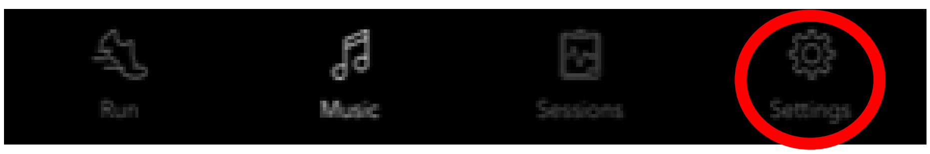
For your first day of testing, please follow the below instructions up to bullet point "h.". You will have free access to the Weav Run application using the link for the duration of the study.

2. **Download the Weav Run application using the following link:**
   - **https://weav.app.link/gait-retraining-study-uwm**
   - **OR scan the QR code**
   - **The icon looks like this →**

13. **Create an account**

14. **Today you will complete your Weav Run with the researcher's phone.**

15. **Before you leave today, go to the settings tab.**



   a. **Hit "Help and Feedback"**
      i. **In the text box, type the following.**
      ii. **You can also use the "Scan Text" feature on your iPhone by holding down the cursor while in the text box.**

I am a participant in the UWM gait retraining study. I will need access to the playlists and the Export feature for this study. Thanks!

16. At your next session, you will be further oriented to the Weav Run Application.

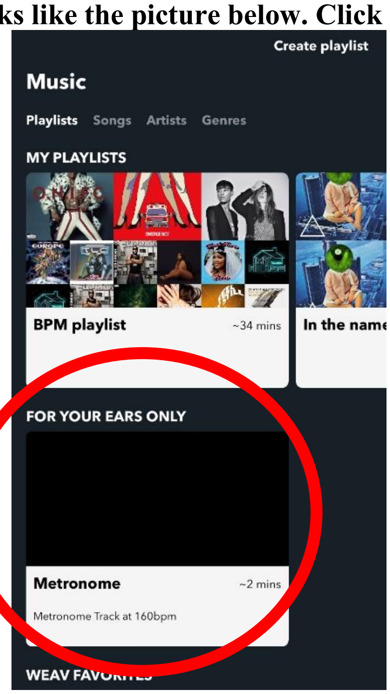
For this study, you will be asked to continue your normal running volume (miles, frequency and/or duration) throughout the next month. We ask that you use the Weav Run App every time you run throughout the gait retraining study. Directions are described below. You can run on a treadmill, indoors on a track, or outdoors. Please only use the playlists you have used in the lab until told otherwise.

Before you start running:

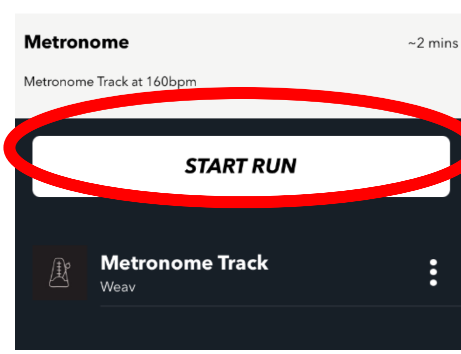
17. Access your playlist

a. Do this by going to the bottom bar of the app screen and selecting the "Music" tab

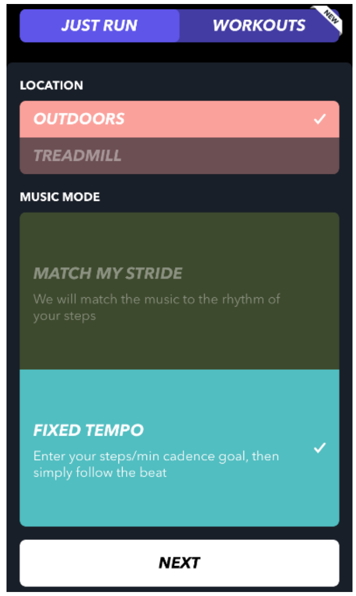
b. You will then see a page that looks like the picture below. Click on "Metronome" playlist.



c. Click on "Start Run".

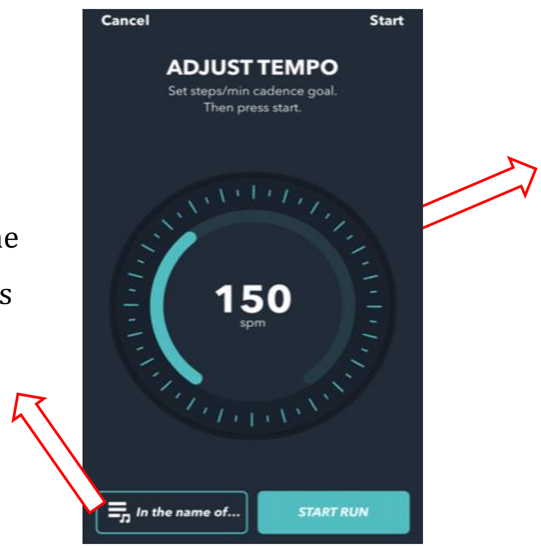


18. You will now hear your metronome start. Before you begin to run, open the Weav Run App. You should see the screen below. If not, make sure you have “Just Run” selected. Select “Treadmill” or “Outdoor” accordingly and “Fixed Tempo”. Then click “Next”.



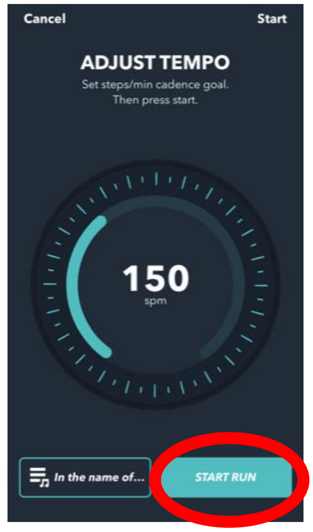
19. Don’t start running just yet!

Make sure this has the name of the metronome playlist. If not, click this button and select the metronome playlist.



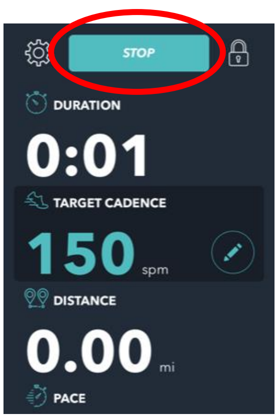
Make sure this number is set to your target step-rate given to you.

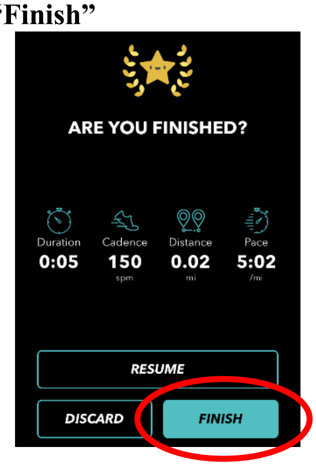
20. Hit Start run Slide or hit the arrow down to get back to the main page shown below and go!



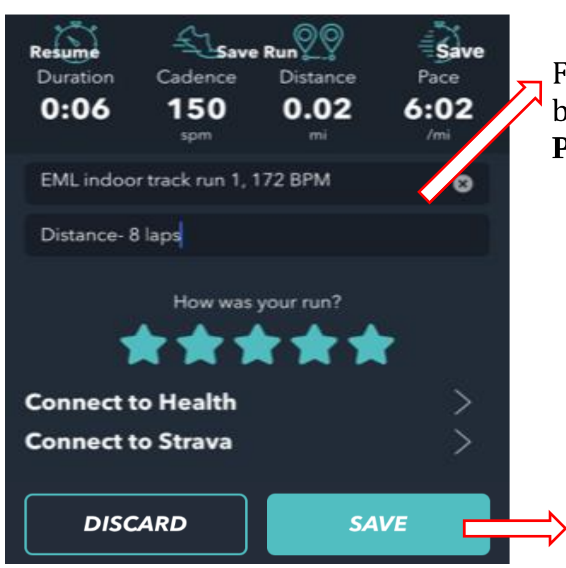
Ending your run:

21. To end your run click the "stop" button at the top. Then click "Finish"





22. Record the run using the following guide



For "Title" input your details below.
ParticipantID_group_run#1

Finally, press save

23. Go to the “sessions” tab at the bottom.

Click on the run you completed today and export to mail.

i. Send to: emlally@uwm.edu
ii. Subject Line: Running Data Participant ID

Appendix H: RPE Scale

Instruction: I want you to rate your perception of exertion or how heavy and strenuous the exercise feels to you. The perception of exertion depends mainly on the strain and fatigue in your muscles and on your feeling of breathlessness or aches in the chest. Look at this rating scale; I want you to use this scale from 6-20, where 6 means “no exertion at all” and 20 means “maximal exertion.” Try to appraise your feeling of exertion as honestly as possible, without thinking about what the actual physical load is. Don’t underestimate it, but don’t overestimate it either. It’s your own feeling of effort and exertion that’s important, not how it compared to other people’s. What other people think is not important either. Look at the scale and the expressions and then give a number. Any questions?

- 9 corresponds to very light. For a normal healthy person, 9 would be like walking slowly at his or her own pace for some minutes.
- 13 on the scale if somewhat hard exercise but still feels okay to continue
- 17 is very hard or very strenuous. A healthy person can still go on, but he or she really has to push him- or herself. It feels very heavy, and the person is very tired.
- 19 on the scale is an extremely strenuous exercise level. For most people, this is the most strenuous exercise they have ever experienced.

6	No Exertion at all
7	Extremely Light
8	
9	Very Light
10	
11	
12	
13	Somewhat Hard
14	
15	Hard (heavy)
16	
17	Very Hard
18	
19	Extremely Hard
20	Maximal Exertion

Appendix I: Email Reminder and Survey

Dear participant,

I am contacting you to provide a friendly reminder to export your Weav Run running data you are recording as part of the research study “Using Music to Modify Step-rate and Running Biomechanics in Healthy Runners”. You can send each of these data exports directly to my email @ emlally@uwm.edu. Unfortunately, if I do not receive your data, I will have to exclude you from the remainder of the study, and you cannot be compensated for your time up to this point. If you have not recorded any data within the Weav Run app, please respond to this email indicating that. If you are having any issues with the recording or exporting of your data, please contact me and I will be happy to help you!

Please complete the survey by following the link below, as well.

https://milwaukee.qualtrics.com/jfe/form/SV_3E3DidexiHWsf2u

Thanks,

Erin

Survey in Qualtrics:

What is your participant number?

[ ]

Did you go for any runs without the Weav Run app?

- Yes
- No

If so, how many runs have you taken without using Weav Run this week? *Please report in a fraction format like so: 1/2 runs completed with Weav Run*. If not, please write n/a.

[ ]

If so, please indicate the number of miles you ran without the Weav run app this week? If not, please write n/a

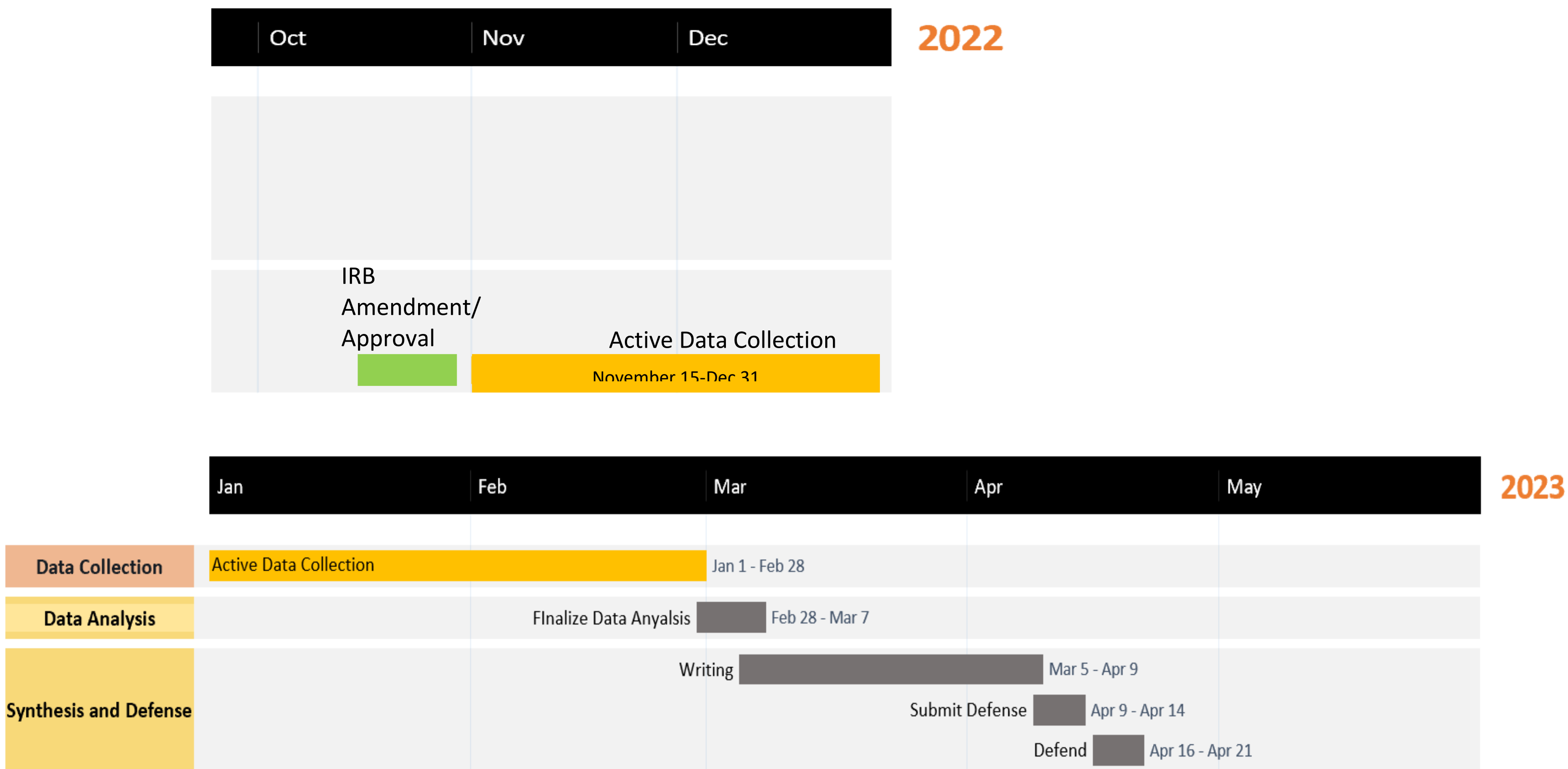
[ ]

Please upload your Weav Run data files to this survey.

[ ]

Appendix J: Timeline

The timeline for the proposed study is depicted below. Active data collection beginning in mid-November 2022 through the end of February 2023. After all data is collected, analysis will take place until approximately mid-March. Writing will begin directly after analysis and is intended to be submitted by mid-April. Defense will then follow. This schedule is based, of course, on how quickly the intended participants are enrolled. There is a potential for carry over into the summer months with degree conferral by August 2023.



Appendix K: Budget and Justification

Item:	Description:	Cost
Universal phone arm bands	12"-16", price per band 10.00, 35 needed	$350.00
3D Motion Analysis expendable supplies		$250
Participant compensation	$50.00 gift cards X 30 participants	$1,500.00
Conference travel and hotel		$450.00
		Total: $2,550.00

Equipment

Armbands are needed to create consistency related to the auditory cue and running data for each participant in the study. I will purchase more bands to account for differences in participant sizes and any breakage that may occur during the intervention.

To collect 3D biomechanical data, we will need some standard expendable supplies. I will be using the the MyoMotion system to collect biomechanical data and use tape to provide extra support for the straps. Adhesive stickers are also recommended for the MyoMotion system inertial measurement unit sensors by the manufacturers to ensure the sensors properly adhere to the participant.

Participant Compensation

I have allocated a large portion of the budget to participant compensation in the form of gift cards.

Conference travel and hotel

I am asking for funds to offset the costs of travel and hotel for when the results of the study are presented at GLATA or NATA.

Appendix L: Pilot Results

Context: Running-related injury (RRI) is often accompanied by long recovery times and high reoccurrence rates. Development of RRI is a barrier to continuing to run so interventions for prevention and treatment of RRI are imperative. Gait retraining is an effective intervention to prevent or treat RRI, reduce loading, and improve movement deviations. Temporospatial gait retraining includes manipulating step-rate and is exclusively accomplished using a metronome. However, many runners prefer to listen to music and foreknowledge of removal of music can impact the ability to perform exercises. It is possible that step-rate modifications can be achieved with tempo of music but first the feasibility of step-rate modification using music must be established. The purpose of this study was to compare group differences between two forms of temporospatial gait retraining (music and a metronome) on step-rate and running biomechanics. **Methods:** 10 individuals (age:33 ± 7.37 years; weight:76 ± 13.98 kg; height:1.70 ± .08 m; average weekly mileage:6.44 ± 9.20 miles) were assigned to two groups (music auditory cue (MUS) or metronome auditory cue (MET)). Participants completed a baseline treadmill running assessment wearing inertial measurement units (IMUs) while peak positive tibial acceleration (PPA) and peak stance phase hip adduction were collected. The researcher then calculated target step-rate (*(preferred step-rate* ∗ *5%) + preferred step-rate= target step-rate*). The WeavRun© phone application allows tempo of selected music to be adjusted and was used to deliver the auditory cueing. The MUS group self-selected music tracks that were tempo adjusted, and the MET group used a metronome track only. Auditory cues were set to the target step-rate and participants were instructed to begin running at the same speed used during baseline. The MET group was told to match foot strikes to beats of the metronome and the MUS group was told to match foot strikes to beats of the music. After five minutes, auditory cues were removed, and participants were instructed to continue running at the target step-rate while posttest data was collected. Group differences in PPA and peak stance phase hip adduction from baseline and posttest time points were analyzed using a series of 2 x 2 repeated measures analysis of variance. **Results:** Both groups decreased PPA from baseline to posttest. There were no main effects for group, nor an interacting for peak hip adduction during stance (Table). **Conclusion:** There were no differences between music and metronome groups, indicating both techniques were effective to increase SR and lower loading during running. Music is a comparable strategy to change step-rate and decrease loading during running that may provide more psychosocial benefits to runners.

Table: Results by time point for both groups.

Variable		Pretest	Posttest	Mean Difference
Step-rate (spm)	MUS	156.80 ± 3.99	167.40 ± .4.80	10.60 ± 2.48
	MET	153.60 ± 3.99	163.20 ± .4.80	9.60 ± 2.48
	COMBINED	**155.20 ± 2.82**	**165.30 ± 3.40**	**10.10 ± 2.01****
PPA (g)	MUS	5.08 ± .56	4.41 ± .73	-.67 ± .89
	MET	4.46 ± .56	3.98 ± .73	-.47 ± .89
	COMBINED	**4.77 ± .40**	**4.20 ± .52**	**-.57 ± .25***
	MUS	11.61 ± 2.79	12.26 ± 1.26	-1.81 ± 2.05

Peak hip adduction (°)	MET	11.39 ± 2.79	9.59 ± 1.26	-.64 ± 2.05
	COMBINED	11.51 ± 1.97	10.92 ± .90	-.59 ± 1.45

spm = steps per minute; MUS= music group; MET= metronome group; PPA = peak positive tibial acceleration; g = gravitational acceleration; **statistically significant at .001; *statistically significant at .05

Appendix M: Instruction Guide

Introductory Run MUS group instruction: “Here is the part when we are going to increase your step-rate by 5%. To aid you in increasing your step-rate we use the Weav Run app and the beats of the music playlist you selected. I have calculated your preferred to be at ___ *let the participant hear what that sounds like* so your target step-rate is now ___ *let the participant hear what that sounds like*. A tip that may help you with this task is to try and match your footfalls to the beats (tempo) of the music, like so *demonstration of researcher marching to the target step-rate while the audible cue is playing*. Do you have any questions, and/or do you understand the goal of the task? Throughout this part, if you want to know how you are doing on the task, feel free to ask me and I will let you know.

Introductory Run MET group instruction: “Here is the part when we are going to increase your step-rate by 5%. To aid you in increasing your step-rate we use the Weav Run app and the beats of the metronome. I have calculated your preferred to be at ___ *let the participant hear what that sounds like* so your target step-rate is now ___ *let the participant hear what that sounds like*. A tip that may help you with this task is to try and match your footfalls to the beats of the metronome, like so *demonstration of researcher marching to the target step-rate while the audible cue is playing*. Do you have any questions, and/or do you understand the goal of the task? Throughout this part, if you want to know how you are doing on the task, feel free to ask me and I will let you know.

Gait retraining sessions MUS group instruction: “Now is the time we are going to practice the new step-rate we introduced in the first session for approximately 15 mins of running. To aid you in increasing your step-rate we use the Weav Run app and the beats of the music playlist you selected. Just a reminder, your target step-rate is now ___ *let the participant hear what that sounds like*. A tip that may help you with this task is to try and match your footfalls to the beats (tempo) of the music, like so *demonstration of researcher marching to the target step-rate while the audible cue is playing*. Do you have any questions, and/or do you understand the goal of the task? An important component of learning the new step-rate is also practicing without the audible feedback so I will remove the feedback after approximately __ mins today. Throughout this part, if you want to know how you are doing on the task, feel free to ask me and I will let you know.

Gait retraining session MET group instruction: “Now is the time we are going to practice the new step-rate we introduced in the first session for approximately 15 mins of running. To aid you in increasing your step-rate we use the Weav Run app and the beats of the metronome. Just a reminder, your target step-rate is now ___ *let the participant hear what that sounds like*. A tip that may help you with this task is to try and match your footfalls to the beats of the metronome, like so *demonstration of researcher marching to the target step-rate while the audible cue is playing*. Do you have any questions, and/or do you understand the goal of the task? An important component of learning the new step-rate is also practicing without the audible feedback so I will remove the feedback after approximately __ mins today. Throughout this part, if you want to know how you are doing on the task, feel free to ask me and I will let you know.

Self-administered gait retraining sessions MUS group instruction: “For this portion of the study, we ask that you use the Weav Run app the same as how we have used it together in the lab each time you run for the next month. It is your choice to add or remove any music to your playlist throughout the next month. You may find it helpful to remember the tips I have provided for you throughout our time in the lab including *previous instruction and additional instruction here*. Do you have any questions, and/or do you understand the goal of the task? An important component of the study is to gain the data you record on your phone while you run so we ask that you try to maintain your previously reported average running mileage of **____** during the next month while using Weav, as well. Once you complete your runs, you can export the data directly to my email address. You may find it helpful to keep track by exporting your run data right after you complete your run or at the end of each week. I will also try to aid you in remembering to export your data by sending an email each week. If you need anything from me throughout this part, you can email or text me directly.

Self-administered gait retraining session MET group instruction: “For this portion of the study, we ask that you use the Weav Run app the same as how we have used it together in the lab each time you run for the next month. You may find it helpful to remember the tips I have provided for you throughout our time in the lab including *previous instruction and additional instruction here*. Do you have any questions, and/or do you understand the goal of the task? An important component of the study is to gain the data you record on your phone while you run so we ask that you try to maintain your previously reported average running mileage of **____** during the next month while using Weav, as well. Once you complete your runs, you can export the data directly to my email address. You may find it helpful to keep track by exporting your run data right after you complete your run or at the end of each week. I will also try to aid you in remembering to export your data by sending an email each week. If you need anything from me throughout this part, you can email or text me directly.

Additional introductory instruction to be given, if needed:
“You may find it helpful to take smaller steps/strides in order to match your footfalls to the beats.”
“Would you find it helpful/prefer if I provided a snapping to the tempo, before beginning?”
“You may think of increasing your step-rate as taking shorter steps while you run.”
“You may think of increasing your step-rate as landing with your heel under your hip.”

Additional instruction throughout the study to be given, if needed or requested:
“You can really focus on those beats and shorten those steps.”
“Your step rate is looking really good!”
“Not quite there, you can try *any of the above cues*…. Yes, look good now.”
“You seem to be right on target.”
“You seem to be slightly faster/or slower than target. You can try *any of the above cues*.”