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Efficacy of an Audio-Based Biofeedback Intervention to Modify Running Gait in Female Runners

by

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Abstract

Introduction: Gait retraining interventions are used to modify foot strike parameters associated with musculoskeletal injuries. Such interventions may prove beneficial if gait modifications are maintained long-term and provide a physiological performance benefit.

Purpose: The primary purpose of this study was to determine whether female recreational runners can use a smartphone decibel app to self-modify gait mechanics associated with injury. The secondary purpose was to determine if such gait modifications are retained beyond the initial training session. The tertiary purpose was to determine if such gait modifications were associated with improved running economy.

Methods: The peak vertical ground reaction force (vGRF), impact transient (IT), maximal instantaneous vertical loading rate (VILR), average vertical instantaneous vertical loading rate (VALR), ground contact time (GCT), and running economy (RE) were collected from subjects during overground and treadmill data collection sessions held Pre-training, Training, and at a 1-week Follow-Up. The gait retraining intervention used a smartphone decibel app to provide biofeedback on the sound intensity of the subject's footfall.

Results: Fifteen female recreational runners were included. There was a significant decrease in vGRF at the Follow-Up Session versus Pre-Training (2.39 vs. 2.34 BW, *p* = .023) and versus Training Session (2.34 vs. 2.30, *p* = .047). There was a significant decrease in VILR between Pre-Training versus Training Sessions (69.70 vs. 62.24 $\mathrm{BW \cdot s^{-1}}$, *p* = .02) and Pre-Training versus Follow- Up Sessions (69.70 vs. 60.35 $\mathrm{BW \cdot s^{-1}}$, *p* = .031). There was not a significant decrease in VO_2 among Sessions (*p* = .308).

Conclusions: Results from this study suggest a gait retraining intervention using a Decibel X app may enable recreational runners to benefit from self-modification of gait biomechanics associated with musculoskeletal injury long-term without an adverse effect on metabolic performance.

Keywords: Gait retraining; Running; Feedback: Ground Reaction Forces; Running Economy

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CHAPTER 1

INTRODUCTION

Long-distance runners commonly suffer from musculoskeletal injuries, such as stress fractures, strains, and sprains, which may significantly impact their training and racing schedules (Fredericson, Jennings, Beaulieu, & Matheson, 2006; Kahanov, Eberman, Games, & Wasik, 2015; C. Milner, Davis, & Hamill, 2005). Female runners are at an increased risk of sustaining stress fractures compared to males (Arendt, Agel, Heikes, & Griffiths, 2003). Lower bone density, a wider pelvis, lower energy availability and menstrual abnormalities might contribute to the greater occurrence of stress fractures in females (Beck et al., 2000; Bennel, Matheson, Meeuwisse, & Brukner, 1999).

In order to heal from a stress fracture, an individual must refrain from impact-related activities for up to 14 weeks which may have detrimental impacts on performance (Creaby & Franettovich Smith, 2016; Crowell & Davis, 2011). In particular, this prolonged recovery period and subsequent rehabilitation may negatively impact cardiovascular fitness and muscular function (Coyle et al., 1984). Additionally, there is a high recurrence rate of stress fracture which further supports the need to mitigate the risk of stress fractures and other musculoskeletal injuries in runners (Crowell & Davis, 2011). Risk factors for stress fractures and other injuries in runners include quantifiable biomechanical features of the running gait, such as, long stride lengths (Hausswirth, Bigard, & Guezennec, 1997), high ground reaction forces (Crowell & Davis, 2011; Tate & Milner, 2017), low step frequency (Hafer, Brown, Demille, Hillstrom, & Garber, 2015; Hobara, Sato, Sakaguchi, Sato, & Nakazawa, 2012) and high tibial accelerations (Creaby & Franettovich Smith, 2016; Crowell & Davis, 2011). Reductions in these variables may help reduce the risk of injury that occurs as a result of the high frequency of ground contacts during running.

Gait retraining might be one strategy to improve biomechanics and reduce the risk of musculoskeletal injuries in long-distance runners. Gait retraining, defined as the modification of suboptimal gait patterns, can be performed by a runner with the aid of running coaches, gait clinics, physical therapists, and/or other trained clinicians to reduce injury risk (Townshend, Franettovich, & Creaby, 2017). With the help of these professionals and specialized equipment, such as force plates and accelerometers, feedback can be provided to the runner to reduce negative biomechanical features of the runner's gait. Several studies have demonstrated the effectiveness of gait retraining utilizing verbal feedback from coaches and clinicians (Phan et al., 2017), visual feedback to reduce tibial accelerations (Crowell & Davis, 2011), and sound/auditory feedback to reduce vertical ground reaction force and loading rates (Tate & Milner, 2017). Despite the success of such biofeedback forms to improve abnormal gait patterns, the need for specialized equipment and trained clinicians limits the use of gait retraining programs examined in previous studies to a smaller population of runners with access to such resources (Crowell & Davis, 2011; Phan et al., 2017; Tate & Milner, 2017). In order to expand the benefits of gait retraining to include a larger population of runners, the efficacy of alternative more accessible methods needs to be investigated.

The current study proposes to use a smartphone app to promote gait modifications. Given the ubiquity of smartphones and free applications to record audio intensity this approach would present an accessible mechanism to modify gait patterns to those otherwise unable to access trained clinicians or specialized recording devices at the clinical or research environments. A runner could utilize their own smartphone device to modify their gait pattern in response to biofeedback upon the sound of their foot impacts. The sound of foot impact, recorded via a decibel meter, will provide a quantitative and visual display of the amplitude of foot impact that may enable the runner to modify their gait to reduce the amplitude and run quietly. Collection of biomechanical variables (vertical ground reaction force, rate of force development, and ground contact time) utilizing a force plate will allow for determination of the efficacy of audio feedback, provided by the decibel X app, to alter running gait and reduce variables associated with injury. This novel gait retraining method might allow runners without access to equipment and/or clinicians to partake in self-regulated gait retraining and extend the length of their running careers.

In addition to the benefit of reduced injury risk, gait retraining may provide a metabolic performance benefit. Due to the high metabolic cost of force production to both support and propel the body forward, reduction of biomechanical factors, such as ground reaction force and ground contact time (Nummela, Keranen, & Mikkelsson, 2007; Saunders, Pyne, Telford, & Hawley, 2009), via gait modification may improve running economy (Anderson, 1996; Hausswirth et al., 1997; Heise & Martin, 2001; Kram & Arellano, 2014). Running economy is defined as the rate of oxygen consumption at a given submaximal running velocity (Conley, Krahenbul, Burkett, & Millar, 1984). This parameter is influenced by variables such as training history, environmental factors, anthropometry, physiology, and gait mechanics (Moore, 2016). Thus, gait retraining may improve running economy via altering the last of these, and thereby reduce the relative intensity of running and provide a performance advantage.

Despite the incidence rate of running-related injuries as high as 85%, running remains to be a popular competitive and recreational sport (Bovens et al., 1989). The efficacy of gait retraining programs to reduce injury rates and improve performance has been well documented. However, the cost of specialized equipment and trained clinicians involved limits the access to such beneficial programs. Feedback provided by a smartphone decibel recording app may bridge a gap in the literature and provide a source of gait retraining in which laboratory-based knowledge is made accessible to the everyday runner concerned about preventing injury and improving performance.

Statement of the Problem

The utilization of force plates and accelerometers in gait retraining programs to quantify changes in biomechanical variables associated with abnormal gait patterns has been well documented. However, a number of runners lack the physical and financial resources to partake in gait retraining programs that feature lab-based tools and knowledgeable clinicians. A more readily available, low-cost alternative is needed to bridge the gap for runners concerned about injury risk and performance without the access to such resources. Therefore, the efficacy of audio feedback provided by an easily accessible smartphone app (e.g., Decibel X) as a gait retraining tool to reduce injury risk and improve running economy will be investigated.

Purpose

The primary purpose of this study is to determine if a gait retraining program using a smartphone decibel recording app can influence gait patterns/stride characteristics to reduce impact force parameters in female runners. The secondary purpose of this study is to determine if any observed changes in biomechanical and/or physiological parameters at the conclusion of the training session are maintained following a one-week period of no intervention at the follow-up session, indicative of learning. The third purpose of this study is to determine if changes in gait pattern/stride characteristics as a result of the gait retraining program are associated with running economy or oxygen consumption during running.

Hypotheses

H_0: Gait retraining using the Decibel X app will not alter a runner's gait patterns/stride characteristics and will not alter their peak vertical ground reaction force, rate of force development, and ground contact time at the post-training session.

H_a: Gait retraining using the Decibel X app will alter a runner's gait patterns/stride characteristics and will reduce their peak vertical ground reaction force, rate of force development, and ground contact time at the post-training session.

H_0: Observed biomechanical and physiological modifications in response to gait retraining will not be maintained following a one-week period of no intervention at the follow-up session.

H_a: Observed biomechanical and physiological modifications in response to gait retraining will be maintained following a one-week period of no intervention at the follow-up session.

H_0: Observed biomechanical modifications in response to gait retraining will not be associated with changes in oxygen consumption during steady-state running.

H_a: Observed biomechanical modifications in response to gait retraining will be associated with lower oxygen consumption during steady-state running.

Delimitations

The delimitations of this study include:

1. Experienced female runners ages 18-40 years old who can complete a 5k race in 18-23 minutes or 10k race in 36-46 minutes.
2. No history of musculoskeletal injuries that impacted running in the last 6 months.
3. No contraindications for exercise as determined by the PAR-Q.

Limitations

The limitations of this study include:

1. Use of a convenience sample.
2. Use of a healthy population of runners limits generalizability of study results to runners with a history of musculoskeletal injury or stress fracture.
3. Use of a motorized treadmill during metabolic data collection may limit generalizability of data to overground running due to greater reliance on the hamstrings to produce propulsive forces during overground running (Saunders et al., 2009).

Assumptions

The following assumptions were made about this study:

1. Honest self-reports of training, injury, and race time history by participants.

Definition of Terms

Running	Form of locomotion including a stance phase, in which the left and right limbs make alternating contacts with the ground, and an aerial phase, in which no limbs touch the ground between each ground contact (Ounpuu, 1994).
Runner	Females, aged 18-40 years old, who can complete a 5k race in 18-23 minutes or a 10k race in 36-46 minutes with no history of musculoskeletal injury impacting running in the last 6 months.
Gait retraining	A strategy utilized to address and modify suboptimal gait patterns that contribute to running-related injuries (Townshend et al., 2017).
Ground reaction force	Recording of the force applied by the body to the ground during contact with a force platform force (Zadpoor & Nikooyan, 2011).
Vertical loading rate	Slope of the initial part of the vertical ground reaction-time curve between footstrike and the vertical impact peak indicating how quickly the vertical component of the ground reaction force reaches the impact peak (Zadpoor & Nikooyan, 2011).

Vertical impact peak	Local maximum between foot strike and maximum force on vertical ground reaction force curve (Crowell & Davis, 2011).
Vertical instantaneous loading rate	Maximum slope of the vertical ground reaction force curve between successive data points in the 20-80% region of the vertical impact peak (Crowell & Davis, 2011).
Vertical average loading rate	Slope of the line through the 20% and 80% points on the vertical ground reaction force curve (Crowell & Davis, 2011).
Running economy	Rate of oxygen consumption at a given submaximal running velocity. Lower oxygen consumption indicative of better running economy (Moore, 2016).

Significance of the Study

Running is a repetitive activity marked by repeated foot contacts with the ground. Higher frequency and magnitudes of these impact events are associated with increased risk of lower-extremity injuries. Gait retraining programs utilizing biofeedback have been developed to alter abnormal gait patterns and reduce negative biomechanical variables associated with injury, such as high loading rates and vertical ground reaction forces (Crowell & Davis, 2011; Phan et al., 2017; Tate & Milner, 2017). For instance, cross-sectional studies have demonstrated that runners with previous stress fractures have significantly greater peak vertical ground reaction forces and vertical loading rates compared to runners with no history of stress fractures (Ferber, Davis, Hamill, Pollard, & Mckeown, 2002; Grimston, Engsberg, Kloiber, & Hanley, 1991; Milner, Ferber, Pollard, Hamill, & Davis, 2006). The reduction in ground reaction forces, rate of force development, and ground reaction times cited by other studies suggests that gait retraining using biofeedback is a valuable tool for injury prevention (Crowell & Davis, 2011; Tate & Milner, 2017). However, the use of specialized equipment and trained clinicians limits the number of runners that may partake and reap the benefits of gait retraining programs. Therefore, the use of a simple smartphone app to monitor impact volume might allow the everyday runner without access to equipment/clinicians to partake in self-regulated gait retraining meant to reduce injury risk and improve running economy.

In addition, the inclusion of a one-week follow-up in the current study will allow for the determination of whether the gait pattern alterations obtained using the app can be maintained long-term, as was demonstrated by Crowell & Davis (2011) using feedback from tibial accelerations. Lastly, previous studies (Crowell & Davis, 2011; Tate & Milner, 2017) have included both male and female runners. However, due to differences in anthropometrics and running mechanics, female runners are at an increased risk of incurring running-related injuries, specifically stress fractures (Bennel et al., 1999).The use of a convenience sample of female runners will provide insight as to whether a similar reduction in biomechanical variables and improvement in running economy can be obtained by females.

CHAPTER 2

LITERATURE REVIEW

Running is a form of locomotion that includes a stance phase, in which the left and right limbs make alternating contacts with the ground, and an aerial phase, in which no limbs touch the ground between each ground contact (Ounpuu, 1994). Inter-individual variations in running gait form, such as foot-strike pattern, stride length, ground contact time, lower limb joint angles, step rate, and neuromuscular factors, contribute to differences in the ground reaction force profile and metabolic cost of running (Moore, 2016). Due to repeated foot contacts with the ground, running gait abnormalities consistent with increasing loading rates/impact forces may be associated with risk of injury (Callahan, 2000). Tibial stress fractures, in addition to strains and sprains, are one of the most common running-related injuries, with an incidence ranging from 4.4-15.6% and a high rate of recurrence (Callahan, 2000). In addition to abnormal stride characteristics, physiology, training, anthropometrics, diet, and female gender are risk factors for injury. The popularity of running has encouraged the development of gait retraining programs to correct gait abnormalities, a modifiable injury risk factor, to assist runners in the prevention and management of injuries. In addition to injury prevention, gait retraining has physiological impacts that may provide a metabolic performance benefit.

Impact of Gait Retraining on Biomechanical Variables

Gait retraining is a strategy used to address and modify suboptimal gait patterns that contribute to running-related injuries (Townshend et al., 2017). Traditionally, gait retraining is performed by a clinician in a laboratory setting using equipment such as force plates and accelerometers. The data acquired from such equipment, such as lower extremity ground reaction forces and/or accelerations at impact, have been used by clinicians to provide auditory and visual feedback to the runner. Such methods have been successful in the modification of gait patterns to increase step frequency (Hafer et al., 2015; Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011; Hobara et al., 2012), decrease ground reaction force parameters (Crowell & Davis, 2011; Phan et al., 2017; Tate & Milner, 2017), decrease tibial accelerations (Crowell & Davis, 2011), and improve running economy (Anderson, 1996; Santos- Concejero et al., 2013).

A widely available and simple form of gait retraining relies on verbal feedback provided by a coach or clinician during and/or after real-time observation and video analysis of an individual’s running form. A coach or clinician may recommend that an individual “take faster steps” or “land softer” to aid in the reduction of loading variables during landing activities (McNair, Prapavessis, & Callender, 2000; Phan et al., 2017; Wernli & Phan, 2016). The effectiveness of verbal feedback was confirmed by a study in which the quantitative relationship between peak sound amplitude, peak vertical ground reaction force (vGRF), and vertical loading rate (VILR) was explored (Phan et al., 2017). Participants performed five overground trials of barefoot running on a runway featuring a force plate under two sound conditions. The peak sound amplitude, defined as the peak sound created between the runner’s foot and ground during the stance phase of running, was measured via a microphone. In the normal sound condition, participants were provided instruction on how to complete the running trials without reference to the sound of their foot impacts. Next, in the quiet sound condition, participants were instructed to complete the running trials as in the normal sound condition but to make a quieter sound when landing (Phan et al., 2017). The results demonstrated that participants had significantly lower peak sound amplitude, vGRF, and VILR during a quiet sound condition compared to a normal sound condition (Phan et al., 2017). Individuals successfully modified their running technique during the quiet sound condition via adoption of a non-rearfoot strike pattern, increased ankle range of motion and decreased peak hip/knee flexion (Phan et al., 2017). Despite the apparent effectiveness of the verbal feedback, results of this study cannot be generalized due to a lack of strong correlation between peak impact sound and peak vGRF/VILR (Phan et al., 2017). This study suggests that verbal feedback may be a valuable tool for reducing loading variables via gait modifications. However, the use of verbal feedback from a clinician is a form of subjective feedback and lacks the quantitative and objective feedback obtained from feedback utilizing force plates and accelerometers.

In addition to verbal feedback, gait retraining using visual feedback has proven effective in the reduction of lower extremity loading rates. For example, Crowell & Davis (2011) provided runners with a visual display of tibial acceleration signals from an accelerometer over a 2-week retraining period. The visual feedback was coupled with verbal instructions to “run softer” to prevent acceleration peaks from rising over 50% of mean peak positive acceleration. These authors noted significant reductions in tibial accelerations, VILR, vertical average loading rate (VALR), and vertical impact peak

(VIP) immediately post-training (Crowell & Davis, 2011). The authors assumed these reductions to be beneficial adaptations that would reduce tibial stress fractures risk (Davis, Milner, & Hamill, 2004; Milner et al., 2006). However, the runners had excessively high impact forces (>8g tibial acceleration) which may have afforded them the opportunity to achieve such reductions in impact variables. Therefore, the results of this study do not extend to runners without excessively high impact forces. Despite this, compared to other intervention studies, these authors included a follow-up session to establish chronic, rather than just acute adaptation. At a 1-month follow-up, reductions in impact force parameters were maintained, suggesting that the visual feedback resulted in a gait pattern that was learned and maintained without further intervention.

Similar results were found in a study in which reductions in tibial accelerations utilizing verbal clinician-based feedback were compared to those obtained using visual tibial accelerometry guided feedback approaches (Creaby & Franettovich Smith, 2016). Significant reductions in tibial peak accelerations were reported in the clinician and tibial accelerometers groups without a significant difference in this measure between groups. Despite a lack of significant difference between groups, it should be noted that visual feedback using tibial accelerometry provided constant and precise feedback throughout the retraining period compared to intermittent and subjective feedback in the verbal feedback condition (Creaby & Franettovich Smith, 2016). Visual feedback utilizing accelerometers is effective in reducing loading variables associated with tibial stress fractures (Davis et al., 2004; Milner et al., 2006) and may help to reduce the risk of injury.

Gait retraining programs have also utilized auditory feedback to correct abnormal gait patterns and mitigate injury risks. Researchers have demonstrated the ability of runners to reduce impact loading following one session of gait retraining with biofeedback on the sound intensity of their footfalls using a noise meter without verbal feedback (Tate & Milner, 2017). That is, the runners were free to choose their running mechanics without specific instruction on how to mitigate impact forces. It was noted that out of fourteen participants, eleven had reductions in VIP, VILR, and VALR by 20%, suggesting that feedback on the volume of one's footfalls led to beneficial biomechanical adaptations (Tate et al., 2017). In contrast to the research of Crowell & Davis (2011) cited earlier, Tate et al. (2017) demonstrated that runners can modify gait patterns and obtain similar reductions in VIP, VALR, and VILR using auditory biofeedback without verbal input from a coach/clinician or specialized equipment. These results provide evidence that advanced equipment, such as accelerometers and force plates used in other studies, may not be needed to afford such reductions in loading variables and gait retraining may be more accessible to those without access to specialized equipment/clinicians. In addition, in contrast to studies that focused strictly on changing footstrike pattern or cadence, the auditory biofeedback allowed runners to experiment with different gait modifications to find the most fitting option for them and resulted in greater reductions in loading rates (Tate & Milner, 2017). However, the long-term effectiveness of auditory biofeedback without verbal input was not explored as this study only included one gait retraining session without subsequent follow-up to determine if learning occurred.

The studies cited above rely on specialized equipment and trained clinicians in controlled laboratory settings. However, an investigation by Hafer et al. (2015) demonstrated the effectiveness of gait retraining to modify and reduce lower extremity loading rates outside of the clinical setting. A six-week self-monitored retraining at a +10% cadence utilizing metronomes/music in a group of six runners reported significant post-training increases in cadence from 82.88 strides/minute to 84.47 strides per minute (Hafer et al., 2015). The increased cadence reduced the risk of injury by reductions in ankle dorsiflexion at initial contact, peak hip adduction angle, and vertical loading rate (Hafer et al., 2015). Of particular significance, this study recognized the limited access to equipment, such as force platforms, and sought to expand gait retraining to include a larger population of runners. Future studies are needed to determine the effectiveness of gait retraining programs using auditory feedback without the use of lab-based tools or clinicians. In addition, Tate & Milner (2017) demonstrated the effectiveness of auditory feedback to reduce loading variables associated with injuries but future studies are needed to determine the long-term effectiveness of such gait retraining programs, as was demonstrated by Crowell & Davis (2011) using visual feedback of tibial accelerations.

Impact of Gait Retraining on Running Economy

Running mechanics influence injury risk but also running economy (RE). RE is defined as the rate of oxygen consumption at a given submaximal running velocity with lower oxygen consumption (VO_2) indicative of better running economy (Moore, 2016). Running economy is influenced by parameters such as training, environment, anthropometry, physiology, and biomechanics (Moore, 2016). Some data suggest runners can improve running economy by as much as 15% through training (Jones, 2006). For example, a case study of Steve Scott, a former American mile record holder, revealed the impact of RE on performance (Conley et al., 1984). Following six months of training, Scott's VO_2max improved from 74.4 to 77.2 mL/kg/min and his RE improved from 48.5 to 45.3 mL/kg/min at a running velocity of 16 km/hour (Conley et al., 1984). The improvements in both VO_2max and RE reduced the relative intensity by 10% and allowed Scott to perform at a lower percentage of his maximum aerobic capacity. The improvements in Scott's performance can be attributed to the improvements in VO_2max and RE achieved via physiological changes in response to training. Scott's success and that of other distance runners suggests the significance of gait retraining programs to modify biomechanics and improve running economy.

Gait retraining efforts alter biomechanical factors such as stride frequency/length, lower limb joint angles, ground reaction forces, and muscle activation/coactivation that influence RE (Saunders et al., 2009). Biomechanical parameters characterizing a more economical runner include shorter ground contact times (Nummela, Keranen, Mikkelsson, 2007; Saunders, et al., 2009), smaller vertical oscillations (Williams & Cavanagh, 1987), longer strides (Hausswirth et al., 1997), smaller changes in velocity during ground contact, and lower peak ground reaction forces (Anderson, 1996). Gait retraining programs that reduce injury risk via reducing vertical ground reaction forces may also provide performance benefits, as ~80% of total oxygen consumption when running is attributed to body weight support and forward propulsion (Kram & Arellano, 2014).

The effect of reduced ground contact time on RE was examined in runners of North African and European descent (Santos-Concejero et al., 2013). Measurement of physiological and biomechanical factors during a maximum incremental running test revealed that the European runners had lower VO_2 consumption at a given speed and significantly shorter ground contact times at increased velocities, indicative of better RE (Santos-Concejero et al., 2013). In addition to ground contact time, longer strides are associated with a better RE (Anderson, 1996). Although no significant differences in stride length were reported by Santo-Concejero et al. (2013), the similar anthropometrics of the North African and European runners may have accounted for the lack of significant differences reported. However, the effect of stride length was investigated in a group of seven male triathletes in the last 45 minutes of a marathon, a triathlon run, and 45 minute isolated run (Hausswirth et al., 1997). Compared to the isolated run, the stride length in the last 45 minutes of the marathon run was significantly lower. The increased VO_2 and energy demand, indicative of impaired RE, were related to the decreased stride length (Hausswirth et al., 1997). Thus, it can be inferred that gait retraining programs that alter stride length to reduce injury risk may also provide a metabolic performance benefit.

Further evidence has been provided to suggest that, in addition to ground contact time and stride length, components of ground reaction forces influence RE. Reflected in the characteristics of the ground reaction force is the activation of muscles for stability and maintenance of forward momentum during ground contact (Heise & Martin, 2001). Excessive changes in momentum in the vertical, anterior-posterior, and medial-lateral directions are considered wasteful and inefficient. The change in momentum is quantified by the linear impulse, defined as the time integral of a force profile. Heise & Martin (2001) demonstrated that net impulse in the medial-lateral direction, indicative of lateral motion/oscillation, and total vertical impulse, indicative of overall muscular support to prevent collapse of the lower limb, influence RE. Following collection of physiological and biomechanical data, analysis revealed significant negative correlations between total vertical impulse and net vertical impulse with RE, respectively. The results provided further evidence that muscle forces needed for support during the stance phase and the time to develop such forces, are metabolically costly.

In conjunction with the benefits of reduced linear impulses, RE is improved as a result of reduced vertical impact peaks. Williams and Cavanagh (1987) determined that more economical runners had lower vertical impact peaks in the vGRF time curve and a more predominant rear foot strike pattern. Results suggested that a rearfoot strike pattern allowed for skeletal structures and footwear to bear the load compared to forefoot strikers that relied on musculature to bear the load. Due to the muscular demands before and during support, the rearfoot strike pattern was characteristic of more economical runners (Williams & Cavanagh, 1987). In contrast, determination of the vGRF and RE of 35 recreational runners concluded that a non-significant and low correlation was found between the vGRF and RE (Adelson, Yaggie, & Buono, 2005). These results suggest that differences in discrete elements of the vGRF are not an accurate explanation for inter-individual differences in RE. Differences in the sample demographics, speed of the steady-state session, and footstrike classification of the participants in the studies by Williams & Cavanagh (1987) and Adelson et al. (2005) may account for the different results obtained regarding the relationship between vGRF and RE. Analysis of the literature suggests that gait retraining programs that modify gait patterns/stride characteristics to reduce wasteful changes in momentum, may improve RE and performance. Thus, future studies that examine gait retraining techniques should also examine indices of RE, to investigate whether gait retraining modalities are associated with subsequent improvements in RE.

Relationship between Gender and Injury Rates

In addition to an abnormal gait pattern, gender is a risk factor for musculoskeletal injuries. Compared to males, females are at a higher risk of stress fracture occurrence due to a lower percentage of lean body mass in the lower limbs, a history of menstrual disturbance, adherence to a low-fat diet, lower bone density, and rear-foot strike pattern (Bennel et al., 1999). Despite the inherent risk factors, the 2017 Runners survey stated that 63% of runners are female and classified as fitness/frequent runners with a minimum of four runs per week (USA, 2017). Previous studies have included both males and females (Crowell & Davis, 2011; Tate & Milner, 2017) in the gait retraining programs and noted reductions in the biomechanical variables of interest. It will be significant in the present study to determine if the same magnitude of reduction in such variables can be found when only females are included. Due to the differences in injury rates between genders, the inclusion of females in the present study will allow for the determination of whether a similar magnitude of reduction in biomechanical (ground reaction forces, rate of force development, ground contact time) and physiological (heart rate, VO_2) variables can be obtained.

Summary

Gait retraining programs can take many forms and can result in modified gait patterns/stride characteristics that may reduce injury risk and improve RE. Gait retraining programs that rely on subjective feedback from trained coaches/clinicians have been shown to reduce vertical ground reaction forces/loading rates (Phan et al., 2017) and lead to an increase in step rate (Hafer et al., 2015) which are associated with decreased risk of injury. In addition, auditory and visual feedback utilizing objective force plate and accelerometer data are effective in reducing vertical impact peaks, loading rates, and peak positive accelerations (Creaby & Franettovich Smith, 2016; Crowell & Davis, 2011; Davis et al., 2004). A reduced injury risk is coupled with the added metabolic performance advantage of reduced running economy that occurs as a result of improved gait patterns (Saunders et al., 2009). Given the benefits of gait retraining programs there is a need for more accessible methods for runners, such as a free smartphone app proposed in the current study.

CHAPTER 3

METHODS

Participants

An *a priori* power analysis was conducted in G*Power (version 3.1.9.4) to determine the sample size needed to examine the efficacy of the gait retraining program. Based on data from previous research (Tate & Milner, 2017), it was determined that 10 participants were needed to adequately power the study. To account for possible dropouts or exclusion from data analysis, fifteen participants were recruited. Eligible participants were female runners 18-40 years old able to complete a 5k race in 18-23 minutes or a 10k race in 36-46 minutes. Exclusion criteria were a history of musculoskeletal injury within the last six months and any contraindications for exercise.

Instruments

A force plate (Bertec 6090-06: Columbus, OH) embedded in the floor of the Biomechanics Laboratory (Professional studies 1163) was used to collect ground reaction forces, loading rates, and ground contact time variables. A timing system (Brower TC-Gate: Draper, UT) was used to ensure that speed was within +/- 5% of the participants preferred running speed during the overground running trials. A standard treadmill (Trackmaster: Newton, KS) was used for the warmup, steady-state running, and cooldown sessions. A chest heart rate monitor (Polar FT1/FT2) was used to collect heart rate data. A metabolic cart (Parvomedics TrueOne Metabolic System: Sandy, UT.) and headset were used to determine the volume of oxygen consumed during steady-state running. A smartphone (iPhone 7, Model Number MNAP2LL/A) with the Decibel X app was used to record audio.

Design and Procedures

Eligible participants gave written informed consent prior to participation in the study and all procedures were approved by the local Institutional Review Board. Participants self-reported training history, race time, and injury history. Contraindications for exercise were assessed via the Physical Activity Readiness-Questionnaire (Warburton, Jamnik, Bredin, Shephard, & Gledhill, 2018) and weekly physical activity was assessed via the International Physical Activity Questionnaire (IPAQ, 2002). Anthropometric data were obtained for scaling biomechanical and physiological measures. The mass, size, and model of each participant's shoe were recorded as shoe design and cushioning level impact gait mechanics (Chambon, Berton, Delattre, Gueguen, & Rao, 2015; Logan, Hunter, Hopkins, Feland, & Parcell, 2010; Pollard, Ter Har, Hannigan, & Norcross, 2018). This study consisted of 3 sessions and participants were asked to wear the same shoe for the duration of the study.

In the initial session (Pre-Training), participants performed a 10-minute warmup at a self-selected pace on a standard treadmill (Trackmaster: Newton, KS). The same treadmill was used for all data collection sessions. Participants then reported their preferred running speed (PRS), defined as the speed at which they felt comfortable running at, for use in the overground and steady-state run sessions. Next, participants completed 5 practice running trials overground at their PRS along a 10 m runway, landing with one foot contacting the middle of a force plate (Bertec 6090-06, Columbus, OH) embedded in the center of this space. Ground reaction forces (GRF) were sampled at

1000 Hz. A pair of timing gates (Brower TC-Gate: Draper, UT) spaced 4 m apart were used to monitor running velocity. The practice trials ensured that participants were familiar with the force plate, able to consistently run at their PRS (within +/- 5%), and make contact with the middle of the force plate with the same foot on each trial without altering their stride to do so (Tate & Milner, 2017). Five acceptable trials that met those criteria were then collected to establish baseline GRF parameters. Following collection of these biomechanical data, researchers assisted the participants to put on a chest heart rate monitor (Polar FT1/FT2) and headset for collection of expired gases (Parvomedics TrueOne 2400 Metabolic System: Sandy, UT). Participants then performed steady state running on the treadmill for 10 minutes at their PRS. The session concluded with a 5-minute cool down at a self-selected speed on the treadmill. All measures collected on this day represented baseline biomechanical and physiological parameters.

Participants returned to the laboratory a minimum of 24 hours after the Pre-Training Session for the Training Session. Participants completed the same 10-minute warm-up as the Pre-Training session. Next, participants ran for 15 minutes at their PRS on the treadmill for the gait retraining. During this run, a smartphone (iPhone 7, Model Number MNAP2LL/A) was placed on the treadmill console to record audio via an app (Decibel X, Skypaw Co. Ltd: Hanoi, Vietnam). To reduce the influence of other noises on the audio recordings, talking and moving of people/objects was restricted in the laboratory. As outlined by Tate & Milner (2017), participants were instructed to run in a way to minimize the sound produced by their footfall without specific instructions on how to accomplish this. Researchers recorded the average, peak, and instantaneous decibel recording every 3 minutes and these were shared with the participant. At the conclusion of the running session, the participants repeated the overground running trials and steady-state treadmill procedure performed in the Pre-Training session. The participant was encouraged to mimic the running pattern adopted during the Training Session during these data collection procedures. Before leaving the laboratory on this day, participants were instructed to use the technique developed during the Training Session throughout the following one-week period prior to returning for their third session.

The final session (Follow-Up) occurred one week after the Training Session and participants completed the same warmup, overground running, and steady-state procedures described above in the Pre-Training Session.

Data Processing

All anthropometric data and survey responses were calculated as mean ± SD. The metabolic equivalent (MET) minutes per week, defined as the amount of energy expended to carry out physical activity, was determined from the IPAQ responses. Total METs and leisure time METs were determined using an algorithm (Patterson, 2005).

Force data were exported as text files to MATLAB (Mathworks, Natick, MA, version R2018a) for processing in a custom script. Force data were filtered with a recursive, digital Butterworth lowpass filter (f_c = 50 Hz). Ground contact was initiated and terminated at a threshold of 10 N. Peak vertical GRF, impact transient, maximal instantaneous vertical loading rate, average vertical loading rate, and ground contact time were identified from each trial and then averaged within each session (Dames, Smith, & Heise, 2017). Peak vertical GRF (vGRF) was the largest force observed during the entire stance phase. Impact transient (IT) was defined as the largest vertical force observed between the initiation of stance and vGRF. Finite difference approximations were used to obtain the instantaneous slope of the vertical GRF curve from 20% to 80% of IT. The peak (VILR) and average (VALR) values of this series were then identified. All force measures were then normalized to bodyweight. Lastly, ground contact time (GCT) was determined as the difference in time from toe-off and initial contact. These methods are similar to a previous gait retraining intervention (Crowell & Davis, 2011). Metabolic data were exported as text files for processing in Excel as a series of 5-second averages. The average relative oxygen consumption ($ml \cdot kg^{-1} \cdot min^{-1}$) during the final 3 minutes of each steady-state run was obtained.

Statistical Analysis

A series of 1x3 (Session) repeated measured ANOVAs were used to compare dependent variables across trials. If assumptions of sphericity were violated a Greenhouse-Geisser adjustment was applied. Effect sizes are reported as partial eta squared and interpreted as small (0.0099-0.0587), medium (0.0588-0.1378) and large (>0.1379) (Richardson, 2011). Post hoc tests were performed with the Bonferroni adjustment for multiple comparisons among Pre-Training, Training, and Follow-Up Sessions. The level of significance was set at 0.05. All statistical procedures were performed using JASP (University of Amsterdam, Amsterdam, Netherlands, Version 0.11.1.0).

CHAPTER 4

MANUSCRIPT

Title: Efficacy of an Audio-Based Biofeedback Intervention to Modify Running Gait in Female Runners

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Abstract

Introduction: Gait retraining interventions are used to modify foot strike parameters associated with musculoskeletal injuries. Such interventions may prove beneficial if gait modifications are maintained long-term and provide a physiological performance benefit.

Purpose: The primary purpose of this study was to determine whether female recreational runners can use a smartphone decibel app to self-modify gait mechanics associated with injury. The secondary purpose was to determine if such gait modifications are retained beyond the initial training session. The tertiary purpose was to determine if such gait modifications were associated with improved running economy.

Methods: The peak vertical ground reaction force (vGRF), impact transient (IT), maximal instantaneous vertical loading rate (VILR), average vertical instantaneous vertical loading rate (VALR), ground contact time (GCT), and running economy (RE) were collected from subjects during overground and treadmill data collection sessions held Pre-Training, Training, and at a 1-week Follow-Up. The gait retraining intervention used a smartphone decibel app to provide biofeedback on the sound intensity of the subject's footfall.

Results: Fifteen female recreational runners were included. There was a significant decrease in vGRF at the Follow-Up Session versus Pre-Training (2.39 vs. 2.34 BW, p = .023) and versus Training Session (2.34 vs. 2.30, p = .047). There was a significant decrease in VILR between Pre-Training versus Training Sessions (69.70 vs. 62.24 $BW \cdot s^{-1}$, p = .02) and Pre-Training versus Follow- Up Sessions (69.70 vs. 60.35 $BW \cdot s^{-1}$, p = .031). There was not a significant decrease in VO_2 among Sessions (p = .308).

Conclusions: Results from this study suggest a gait retraining intervention using a Decibel X app may enable recreational runners to benefit from self-modification of gait biomechanics associated with musculoskeletal injury long-term without an adverse effect on metabolic performance.

Keywords: Gait retraining; Running; Feedback: Ground Reaction Forces; Running Economy

1. Introduction

Running is a locomotion pattern marked by alternating stance phases where one foot is in contact with the ground and an aerial phase (Ounpuu, 1994). Ground reaction forces, particularly during the initial loading of the limb during stance, are associated with musculoskeletal injuries such as stress fractures. Stress fractures are most evident in the lower limb, with tibial stress fractures accounting for 35% to 49% of all stress fracture cases in runners (Matheson et al., 1987; McBryde, 1985). The prolonged recovery period for a stress fracture, in which an individual must refrain from running, has a significant impact on overall performance manifested as a decrease in cardiovascular and muscular fitness (Coyle et al., 1984). Preventing stress fractures is ideal as this class of injury has a high rate of recurrence and can have a chronic, negative effect on training and racing schedules.

The etiology of stress fractures is multifactorial. Risk factors include older age, female gender, history of stress fracture, low physical fitness level, and rapid progression in weight-bearing training volume and intensity (Arendt, Agel, Heikes, & Griffiths, 2003; Battaloglu, 2011; Bennel & Brukner, 1997; Bennell, Malcolm, & Thomas,n.d.; Jacobs, Cameron, & Bojescul, 2014). Greater peak forces and rates of force development during early stance phase are biomechanical indicators of an increased risk of stress fracture (Crowell & Davis, 2011; Grimston, Engsberg, Kloiber, & Hanley, 1991; Milner, Ferber, Pollard, Hamill, & Davis, 2006; Tate & Milner, 2017). These vertical force parameters may be particularly important for female runners, who are at greater risk to suffer stress fractures (Grimston et al., 1991; Milner et al. 2006). While some of the above risk factors are not modifiable, runners can modify their gait pattern to reduce their impact force characteristics.

Gait retraining programs meant to alter running gait mechanics have come in a variety of forms but commonly aim to reduce stress fracture risk. Previous interventions utilized verbal feedback from coaches and clinicians (Phan et al., 2017), presented records of tibial accelerations to the runner (Crowell & Davis, 2011), and instructed the runner to reduce the volume of their foot strike (Tate & Milner, 2017). Each of these methods were effective at reducing lower extremity loading variables associated with injury (Crowell & Davis, 2011; Phan et al., 2017; Tate & Milner, 2017). Despite the noted reductions in variables associated with stress fracture risk, the need for trained clinicians and specialized equipment limits the application of many of these approaches as the typical runner may lack access and/or funds to afford a coach, visit a running gait clinic, or possess the knowledge to interpret biomechanical data. Thus, the least technical method listed above (i.e., volume of footstrike) represents an attractive form of biofeedback that has promise to benefit the recreational runner.

While many have investigated the potential benefits of gait modification from an injury perspective, it is less common to observe the potential changes in running economy (RE) associated with the new gait pattern. RE is defined as the volume of oxygen consumed at a given sub-maximal running velocity (Moore, 2016). Inter-individual variations in RE are attributed to training, anthropometry, physiology, and biomechanics (Moore, 2016). Therefore, gait retraining interventions may not only prove beneficial for reducing injury risk but also in providing physiological benefits as reducing impact forces is associated with improved RE (Anderson, 1996; Hausswirth et al., 1997;

Heise & Martin, 2001; Kram & Arellano, 2014). Indeed, supporting bodyweight and propelling the body forward account for ~80% of the total oxygen consumption of running (Kram & Arellano, 2014). Therefore, programs that encourage a reduction in ground contact time and an increase in stride length may correlate to improvements in RE (Anderson, 1996; Santos-Concejero et al., 2013) However, contradictions in the literature exist as gait modifications intended to reduce injury risk have caused a negative impact on RE (Townshend, Franettovich Smith, & Creaby, 2017) and no impact on RE (Clansey, Hanlon, Wallamce, Nevill, & Lake, 2014; Roper, Doerfler, Kravitz, & Dufek, 2017). The effects of gait retraining warrant additional investigation as gait modifications that reduce injury risk may not be desirable if such modifications result in impaired RE (Moran & Wager, 2020).

The scope of biofeedback interventions to improve suboptimal gait patterns is promising but requires additional attention. Previous investigations selected runners with increased loading variable measurements at baseline only (Crowell & Davis, 2011), used specialized equipment and required trained clinicians (Crowell & Davis, 2011), utilized a mixed sample of males and females despite anatomical differences between genders (Crowell & Davis, 2011; Phan et al., 2017; Tate & Milner, 2017), and did not include a retention test to determine if gait alterations were maintained, thus not indicating a learning effect (Tate & Milner, 2017). To expand the meaningfulness and scope of gait interventions, given the ubiquity of smart phones capable of measuring and reporting decibels, a simpler and more convenient measure (i.e., foot strike volume) to motivate reductions in impact forces via self-modification of the gait pattern is desirable. Additional exploration is necessary to: 1) Evaluate potential benefits of this method in recreational runners; 2) Determine if the observed modifications are associated with a more economical gait; and 3) Determine if gait modifications persist beyond the acute training session itself. Therefore, the purpose of the study was to determine if a gait retraining program using a smartphone decibel recording app can promote reductions in impact force parameters in female runners. We hypothesized that peak vertical ground reaction force, rate of force development, ground contact time, and oxygen consumption would be reduced immediately following a gait retraining session and that these changes would persist at a 1-week follow-up session.

2. Methods

2.1 Participants

An *a priori* power analysis was conducted in G*Power (version 3.1.9.4) to determine the sample size needed to examine the efficacy of the gait retraining program. Based on data from previous research (Tate & Milner, 2017), it was determined that 10 participants were needed to adequately power the study. To account for possible dropouts or exclusion from data analysis, fifteen participants were recruited. Eligible participants were female runners 18-40 years old able to complete a 5k race in 18-23 minutes or a 10k race in 36-46 minutes. Exclusion criteria were a history of musculoskeletal injury within the last six months and any contraindications for exercise.

2.2 Experimental Procedure

Eligible participants gave written informed consent prior to participation in the study and all procedures were approved by the local Institutional Review Board. Participants self-reported training history, race time, and injury history. Contraindications for exercise were assessed via the Physical Activity Readiness-Questionnaire

(Warburton, Jamnik, Bredin, Shephard, & Gledhill, 2018) and weekly physical activity was assessed via the International Physical Activity Questionnaire (IPAQ, 2002). Anthropometric data were obtained for scaling biomechanical and physiological measures. The mass, size, and model of each participant's shoe were recorded as shoe design and cushioning level impact gait mechanics (Chambon, Berton, Delattre, Gueguen, & Rao, 2015; Logan, Hunter, Hopkins, Feland, & Parcell, 2010; Pollard, Ter Har, Hannigan, & Norcross, 2018). The study included 3 sessions and participants were asked to wear the same shoe for the duration of the study.

In the initial session (Pre-Training), participants performed a 10-minute warmup at a self-selected pace on a standard treadmill (Trackmaster: Newton, KS). The same treadmill was used for all data collection sessions. Participants then reported their preferred running speed (PRS), defined as the speed at which they felt comfortable running at, for use in the overground and steady-state run sessions. Next, participants completed 5 practice running trials overground at their PRS along a 10 m runway, landing with one foot contacting the middle of a force plate (Bertec 6090-06, Columbus, OH) embedded in the center of this space. Ground reaction forces (GRF) were sampled at 1000 Hz. A pair of timing gates (Brower TC-Gate: Draper, UT) spaced 4 m apart were used to monitor running velocity. The practice trials ensured that participants were familiar with the force plate, able to consistently run at their PRS (within +/- 5%), and make contact with the middle of the force plate with the same foot on each trial without altering their stride to do so (Tate & Milner, 2017). Five acceptable trials that met those criteria were then collected to establish baseline GRF parameters. Following collection of these biomechanical data, researchers assisted the participants to put on a chest heart rate monitor (Polar FT1/FT2) and headset for collection of expired gases (Parvomedics TrueOne 2400 Metabolic System: Sandy, UT). Participants then performed steady state running on the treadmill for 10 minutes at their PRS. The session concluded with a 5-minute cool down at a self-selected speed on the treadmill. All measures collected on this day represented baseline biomechanical and physiological parameters.

Participants returned to the laboratory a minimum of 24 hours after the Pre-Training Session for the Training Session. Participants completed the same 10-minute warm-up as the Pre-Training session. Next, participants ran for 15 minutes at their PRS on the treadmill for the gait retraining. During this run, a smartphone (iPhone 7, Model Number MNAP2LL/A) was placed on the treadmill console to record audio via an app (Decibel X, Skypaw Co. Ltd: Hanoi, Vietnam). To reduce the influence of other noises on the audio recordings, talking and moving of people/objects was restricted in the laboratory. As outlined by Tate & Milner (2017), participants were instructed to run in a way to minimize the sound produced by their footfall without specific instructions on how to accomplish this. Researchers recorded the average, peak, and instantaneous decibel recording every 3 minutes and these were shared with the participant. At the conclusion of the running session, the participants repeated the overground running trials and steady-state treadmill procedure performed in the Pre-Training session. The participant was encouraged to mimic the running pattern adopted during the Training Session during these data collection procedures. Before leaving the laboratory on this day, participants were instructed to use the technique developed during the Training Session throughout the following one-week period prior to returning for their third session.

The final session (Follow-Up) occurred one week after the Training Session and participants completed the same warmup, overground running, and steady-state procedures described above in the Pre-Training Session.

2.3 Data Analysis

All anthropometric data and survey responses were calculated as mean ± SD. The metabolic equivalent (MET) minutes per week, defined as the amount of energy expended to carry out physical activity, was determined from the IPAQ responses. Total METs and leisure time METs were determined using an algorithm (Patterson, 2005).

Force data were exported as text files to MATLAB (Mathworks, Natick, MA, version R2018a) for processing in a custom script. Force data were filtered with a recursive, digital Butterworth lowpass filter (f_c = 50 Hz). Ground contact was initiated and terminated at a threshold of 10 N. Peak vertical GRF, impact transient, maximal instantaneous vertical loading rate, average vertical loading rate, and ground contact time were identified from each trial and then averaged within each session (Dames, Smith, & Heise, 2017). Peak vertical GRF (vGRF) was the largest force observed during the entire stance phase. Impact transient (IT) was defined as the largest vertical force observed between the initiation of stance and vGRF. Finite difference approximations were used to obtain the instantaneous slope of the vertical GRF curve from 20% to 80% of IT. The peak (VILR) and average (VALR) values of this series were then identified. All force measures were then normalized to bodyweight. Lastly, ground contact time (GCT) was determined as the difference in time from toe-off and initial contact. These methods are similar to a previous gait retraining intervention (Crowell & Davis, 2011). Metabolic data were exported as text files for processing in Excel as a series of 5-second averages. The average relative oxygen consumption ($ml·kg^{-1}·min^{-1}$) during the final 3 minutes of each steady-state run was obtained.

A series of 1x3 (Session) repeated measured ANOVAs were used to compare dependent variables across trials. If assumptions of sphericity were violated a Greenhouse-Geisser adjustment was applied. Effect sizes are reported as partial eta squared and interpreted as small (0.0099-0.0587), medium (0.0588-0.1378), and large (>0.1379) (Richardson, 2011). Post hoc tests were performed with the Bonferroni adjustment for multiple comparisons. The level of significance was set at 0.05. All statistical procedures were performed using JASP (University of Amsterdam, Amsterdam, Netherlands, Version 0.11.1.0).

3. Results

Descriptive characteristics are presented in Table 1. Participants reported a high level of physical activity as indicated by the leisure time METS (3765.19 ± 3652.97 min) and total METS 4902.42 ± 4480.14 min) (IPAQ, 2002). The IPAQ scores of two participants were excluded due to errors in completing the questionnaire.

There was a significant decrease in vGRF ($F_{1.41,19.735} = 5.634$, $p = .019$, partial $\eta^2 = .287$) across Sessions (Table 2). Post hoc tests revealed a significant decrease in vGRF between Pre-Training versus Follow-Up Sessions ($p = .023$) and Training versus Follow-Up Sessions ($p = .047$). There was a significant decrease in VILR ($F_{2,28} = 6.075$, $p = 0.006$, partial $\eta^2 = 0.303$) among Sessions (Table 2). Post hoc tests revealed a significant decrease in VILR between Pre-Training and Training Sessions ($p = .02$) and Pre-Training versus Follow-Up sessions ($p = .031$). No significant difference in VILR was found between Training and Follow-Up Sessions ($p = 1.0$). There was not a significant difference in VALR ($F_{2,28} = 2.272$, $p = .122$, partial $\eta^2 = .140$) among Sessions (Table 2). Although insignificant, there was a trend toward lower VALR from Pre-Training to Follow-Up Session ($p = 0.324$). There was not a significant difference in IT ($F_{2,28} = 0.742$, $p = .485$, partial $\eta^2 = 0.050$) among sessions. There was a significant difference in GCT ($F_{2,28} = 4.672$, $p = .018$, partial $\eta^2 = .250$). However, post hoc tests did not reveal a significant difference in GCT between Pre-Training and Training Sessions ($p = .280$), Pre-Training and Follow-Up Sessions ($p = .051$), nor Training and Follow-Up Sessions ($p = .693$). Analysis of the metabolic data revealed no significant differences in VO_2 among sessions ($F_{2,28} = 1.228$, $p = .308$, partial $\eta^2 = .081$).

Table 1. Participant Demographics

Parameter	Mean (SD)	Minimum	Maximum
Age (years)	23.93 (6.76)	18	39
Mass (kg)	56.31 (6.55)	43.99	70.99
Height (cm)	164.78 (4.44)	155	170
PRS ($m \cdot s^{-1}$)	2.92 (0.25)	2.46	3.26
Years of Running	8.53 (3.74)	15	2
Miles$\cdot$week^{-1}	24.87 (15.68)	50	6
Leisure-METS (min)	3765.19 (3652.97)	720	8640
Total-METS (min)	4902.42 (4480.14)	9363	1005

Abbreviations: METS, metabolic equivalent for task; PRS, preferred running speed. Values are reported as mean ± SD.

Table 2. Force and Metabolic Data at Pre-Training, Training, and Follow-Up Sessions. Mean (SD)

Parameter	Pre-Training	Training	Follow-Up
vGRF (BW)	2.39 (0.19)	2.34 (0.23)	2.30 (0.24)$^{*+}$
IT (BW)	1.89 (0.49)	1.77 (0.56)	1.78 (0.52)
VILR ($BW \cdot s^{-1}$)	69.70 (21.62)	62.24 (22.68)	60.35 (19.30)$^{*+}$
VALR ($BW \cdot s^{-1}$)	46.65 (17.87)	42.82 (16.12)	40.58 (13.94)
GCT (s)	0.27 (0.03)	0.28 (0.04)	0.28 (0.03)
VO_2 ($ml \cdot kg^{-1} min^{-1}$)	39.32 (5.75)	39.58 (5.19)	40.15 (5.64)

Abbreviations: BW, bodyweight; vGRF, peak vertical force; IT, impact transient; VILR, vertical instantaneous loading rate; VALR, vertical average loading rate; GCT, ground contact time.

Note: * *indicates a significant difference from Pre-Training and* $^+$ *indicates a significant difference from Training Session.*

4. Discussion

The current study examined whether a gait retraining program using a smartphone decibel recording app could promote acute and retained reductions in impact force parameters and RE in female runners. Results indicated that the gait retraining program reduced ground reaction forces but not ground contact time and RE. Notably, reductions in ground reaction forces persisted 1-week following the initial gait-retraining program. This is the first study to observe whether a gait retraining program using a decibel app might lead to long term reductions in vertical force parameters. Thus, our study supports the efficacy of a gait retraining program that uses sound-intensity feedback of a runner's footfalls in recreational female runners which may reduce injury risk.

The vGRF and VILR were significantly reduced following the initial gait retraining program and persisted at the 1-week follow up session. These reductions agree with outcomes from previous research implementing accelerometers to encourage softer foot strike in runners (Crowell & Davis, 2011). These authors reported 30% reductions in VILR whereas we observed a 15% reduction between Sessions. The inclusion of high impact runners (>8 g peak positive tibial acceleration), with a greater opportunity to reduce impact forces, compared to the average reactional runner in our study, may explain the difference in the magnitude of reduction between studies. The reduction in VILR is also in agreement with the findings of Tate & Milner (2017) in which a 34% reduction in VILR was found immediately following gait retraining utilizing a decibel meter. As discussed above, the larger reduction in VILR between sessions by Tate & Milner (2017) may be due to the inclusion of high-impact runners with a VILR greater than 85-BW/s threshold at baseline, which likely afforded them the opportunity for a greater reduction in VILR. Additionally, their study did not include a Follow-Up Session and it is thus unclear if reductions of that magnitude would be maintained long-term. Although insignificant, a trend toward lower VALR was found among Sessions which was expected based on the results of those studies (Crowell & Davis, 2011; Tate & Milner, 2017). Our study suggests that reductions in loading variables are feasible without the need for specialized equipment or clinician feedback. The significant reduction in VILR and the maintenance of such reduction after a 1-week interim, supports the use of a readily accessible smartphone app to provide biofeedback and potentially reduce injury risk in recreational runners.

While a significant reduction in IT was not found, there was a trend toward lower IT across Sessions. A significant reduction in IT was expected in this study to be consistent with the findings of previous gait retraining studies (Crowell & Davis, 2011; Tate & Milner, 2017). A smaller reduction in IT of 6% was found between Pre- and Post-Training Sessions compared to larger reductions of 20% (Crowell & Davis, 2011) and 28% (Tate & Milner, 2017) previously reported. The smaller reductions found in this study may be attributed to differences in participant footstrike patterns which impact lower extremity kinematic and kinetic characteristics. For example, although not analyzed in our study, Crowell & Davis (2011) selected runners with a rearfoot strike (RFS) and excluded midfoot strike (MFS) and forefoot strike (FFS) runners. The vertical GRF profile of a RFS runner will include a high rate of loading and IT as the heel hits the ground first (Lieberman et al., 2010). In contrast, the profile of a MFS or FFS runner is characterized by the absence of an IT and reduced loading rate, as the ball and heel of the foot land simultaneously or the ball of the foot lands first, respectively. Therefore, differences in foot strike pattern among participants in this study and those of Crowell & Davis (2011) may account for the difference in the magnitude of reduction in IT.

Contrary to the expected result, no significant reduction in GCT was found among Sessions. GCT has been targeted in previous gait interventions via alterations in cadence, vertical oscillation (Adams, Pozzi, Willy, Carrol, & Zeni, 2018), and stride length (Santos-Concejero et al., 2013). In this study, no specific gait modification was targeted and participants self-selected a modification to reduce the volume of their footfall. The type of technique selected by the participant may have impacted the GCT as a previous study reported reductions in ground contact time in a high cadence condition but increases in GCT in a low oscillation condition (Adams et al., 2018). Furthermore, previous work has demonstrated the relationship between stride length, which impacts GCT, and RE (Saunders, Pyne, Telford, & Hawley, 2009). Gait modifications that lengthen or shorten stride length beyond an individual's preferred stride length, increase VO_2 and negatively impact RE (Saunders et al., 2009). Therefore, the reduction in vertical GRF in the current study, without an influence on GCT, suggests that gait modifications can be made without negatively impacting running performance.

There was not a significant reduction in VO_2 among Sessions despite reductions in loading variables. It was expected that such reductions in loading variables via gait modifications would correlate to improvements in RE due to the metabolic cost of body weight support and forward propulsion while running (Anderson, 1996; Kram & Arellano, 2014; Santos-Concejero et al., 2013). Limited research is available regarding the effects of gait modifications on RE and previous studies have reported both negative impacts (Townshend et al., 2017) and no impacts (Clansey, Hanlon, Wallace, Nevill, & Lake, 2014; Roper, Doerfler, Kravitz, Dufek, & Mermier, 2017) post gait retraining. However, the type of gait retraining program implemented may explain differences in the impact on RE. For example, when participants were instructed to reduce tibial accelerations, an increase in VO_2 was reported (Townshend et al., 2017) but no such increase was reported when instructed to transition from a RFS to FFS (Roper et al., 2017). This suggests that the technique used during gait retraining to reduce injury risk may impact oxygen consumption and performance. Gait retraining using a decibel recording app in this study enabled participants to self-select a running gait modification to reduce the sound of their footfall and may have resulted in the adoption of a naturally economical modification with no adverse effect on RE. The ability for the gait retraining program using the smartphone app to reduce loading variables associated with injury, without adversely effecting RE, suggests that runners may be more likely to adopt gait alterations as a long-term injury prevention strategy.

A strength of this study is the use of a free smartphone app to provide biofeedback to promote gait modifications without the need for trained clinicians or specialized equipment. However, force data were collected separately during overground running while metabolic data were collected during a treadmill run. To account for differences between overground and treadmill running, future studies should include simultaneous force and metabolic data collection on an instrumented treadmill. A second strength of the study was the inclusion of a Follow-Up session 1-week after the initial Training Session to determine if gait modifications can be maintained. However, future studies should include additional Follow-Up sessions as new running mechanics may require time with which to adapt (Adams et al., 2018). Further, additional Follow-Up Sessions may explain the lack of change in RE as adoption of new gait mechanics may incur increased metabolic demands (Adams et al., 2018). A third strength of the study was the inclusion of female runners, with an inherent increased risk of stress fracture compared to males. However, caution should be taken in the consideration of gait retraining as an injury prevention technique as injury risk was not directly measured. Lastly, future studies should determine if such reductions can be obtained by runners experiencing pain or recovery from injury as a sample of healthy, female runners was utilized.

5. Conclusion

The results of this study support the use of a smartphone app to provide biofeedback to runners as a gait retraining method. The significant reductions in vGRF and VILR suggest that reductions in impact loading variables can be achieved without the use of specialized equipment or trained clinicians. These reductions may enable the recreational runner to reduce the risk of musculoskeletal injury, especially stress fractures. The maintenance of such reductions at a 1-week follow up suggests the retention of the gait modification and potential long-term benefits of the retraining intervention. Lastly, the lack of impact on RE, despite gait modifications that reduced loading variables, suggests that injury risk can be mitigated without an adverse effect on performance.

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Conflict of Interest Statement

The authors have no conflicts of interest.

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Appendix A – Informed Consent

CONSENT TO PARTICIPATE AS A SUBJECT

IN A RESEARCH STUDY

Project Title: Efficacy of a Gait Retraining Program using a Smartphone App in Female Runners

You are invited to participate in a research project about retraining your running gait by using information about how loud your footfalls are. Your informed consent is requested if you wish to participate as a research subject in this project. Before you consent to participate, please read the following details of the study so that you fully understand what your involvement will be and what risks and benefits you may experience as a participant in this research study.

This research is being conducted by the following members of the Kinesiology department at SUNY Cortland:

- Sarah Rothstein - graduate student, sarah.rothstein@cortland.edu, (845) 238-1751
- Jacqueline Augustine, Ph.D. - faculty, jacqueline.augustin@cortland.edu, (607) 753-1017
- Kevin Dames, Ph.D. - faculty, kevin.dames@cortland.edu, (607) 753-4356
- Larissa True, Ph.D. - faculty, larissa.true@cortland.edu, (607) 753-4562

Eligibility

To participate in this study, you must be:

- female
- 18-40 years old
- able to run a 5k race in 18-23 minutes or 10k race in 36-46 minutes
- familiar with treadmill running
- free of any muscle/bone injury that would impact your running in the last 6 months
- free of any condition that serves as a reason not to participate in exercise (i.e., any cardiovascular, respiratory, or musculoskeletal impairment)

Purpose and brief description

The present study seeks to determine if a gait retraining program using a smartphone app (Decibel X) can change female runners' gait patterns to reduce the forces between their feet and the ground. A second aim of this study is to determine if changes in the runners' gait patterns due to the gait retraining program result in better running economy. A third aim of this study is to determine if changes in gait pattern or running economy persist one-week after gait retraining.

Your involvement as a participant

All data collection sessions will take place in the Biomechanics Laboratory (Professional Studies, Room 1163) and the Exercise Physiology Laboratory (Professional Studies, Room 1144E). Your involvement will include **three** sessions. Specific details of the testing sessions are outlined below.

1. **Initial Session.** You will report to the Exercise Physiology Laboratory. The researcher will describe the study to you and ask you to read and sign this informed consent. The researcher will then ask questions to determine if you are eligible to participate in the study. If you are eligible, you will then complete a section of a questionnaire about your current health status and history to determine your readiness to exercise (PAR-Q+). Eligible participants will then complete a questionnaire about your health-related physical activity (IPAQ). Next, the researcher will measure your height, your weight, and your running shoe's weight. Your running shoe size, shoe make, and model will also be recorded. These data will be used to scale the biomechanical and physiological data collected.

   You will warm up with a 10-minute treadmill run at a speed of your choice. You will then walk to the Biomechanics Laboratory where you will practice running at your self-reported preferred running speed (the speed you are comfortable running at) across a force plate set in the floor. You will do this 5 times. These 5 practice trials will help you feel what it is like to run across the force plate while contacting the middle of the force plate with your foot and keeping your running speed close to (within 5% above or below) your self-reported preferred running speed. After the 5 practice trials, you will complete 5 more trials at your preferred running speed over the force plate. The force plate will measure the forces exerted by the ground on your foot during running.

   Next, you will return to the Exercise Physiology Laboratory where you will run on a treadmill for 10 minutes at your self-reported preferred running speed. You will wear a heart rate monitor around your chest to record your heart rate. You will also be fitted with a headset and breathe through its mouthpiece while you run. Your expired air will be analyzed to measure how much oxygen you consume during the run. After the 10 minute run, you will have a 5-minute cool down run at a speed of your choice on the treadmill.

2. **Training Session.** At least 24 hours after the initial session, you will return to the Biomechanics Laboratory for the training session. You will wear the same running shoes you wore previously. You will do a 10-minute warmup run at a speed of your choice on a treadmill. You will then be asked to run for 15 minutes at your preferred running speed on a treadmill. During this run, a smartphone will be placed on the treadmill console. The smartphone app, Decibel X, will record

the sound of your feet hitting the treadmill and will display graphically and numerically how loud the sounds are in decibels. You will be instructed to run in a way to minimize the sound produced by your footfalls without specific instructions on how to do so.

At the end of the 15-minute training session, you will go to the Biomechanics Lab to perform the 5 overground trials while running across a force plate. Force data will be recorded during these 5 trials. You will then return to the Exercise Physiology Lab and complete a 10-minute treadmill run while your heart rate and expired air are recorded and analyzed. During these 5 overground trials and the 10-minute treadmill run you will try to utilize the gait pattern you developed during the training session to reduce the sound of your footfalls. At the end of the 10-minute treadmill run, you will cooldown for 5 minutes at a speed of your choice.

During any training runs over the next week between the training and follow-up sessions, you will try to use the gait pattern you developed during the training session to reduce the sound of your feet hitting the ground. You will be asked to wear the same running shoes during any training runs during this week.

3. **Follow-up Session.** One week after the training session, you will return to the laboratory for the follow-up session. You will wear the same running shoes and will warm-up for 10 minutes at a speed of your choice on a treadmill. As was performed in the initial and training sessions, you will complete the 5 overground trials across the force plate and 10-minute treadmill run while your heart rate and expired air are analyzed. At the end of the 10-minute treadmill run, you will cooldown for 5 minutes at a speed of your choice.

Before agreeing to participate you should understand the following:

- **Your participation is completely voluntary.** You are free to withdraw from this study at any time without penalty, even after you begin participation.
- **Duration of participation**. Your participation in the study will occur on 3 different days over a period of 8-10 days for about 45-60 minutes on each day.
- **Confidentiality.** To ensure privacy and confidentiality, all data and information collected from you will be de-identified. An identification number will be used on all data collection forms and in all data collection software records. This form and the completed IPAQ, PAR-Q+, and VARK questionnaires will be securely stored in a locked office.
- **Risks.** Potential risks of participating in this study are minimal. Participation will include running on a treadmill and overground over a force plate. As with any exercise, potential for fatigue, localized muscle soreness, and/or falls are possible. A researcher will be beside the treadmill at all times should you need the treadmill

to slow down or stop. The warm-up and cool-down runs will help reduce the risk of strains/sprains. The heartrate monitor electrodes and the headset mouthpiece will be cleaned and sanitized before each use.

- **Benefits**. Knowledge of your biomechanical and physiological responses to running may enable you to make better informed choices in training intensities. Corrections of abnormal gait patterns/stride characteristics that may cause an injury may extend your running career and prevent the negative physical/psychological consequences associated with injury.
- **Contact Information**. If you have any questions concerning the purpose or results of this study, you may contact the principal researcher, Sarah Rothstein, or any of the other researchers listed on the first page of this form. Their contact information is also listed on the first page of this form. The SUNY Cortland Institutional Review Board has approved this study. For questions or concerns about your rights as a research participant, contact the SUNY Cortland Institutional Review Board by email at irb@cortland.edu, or by phone 607-753-2511.

I ____ have read the description of the study for which this consent is requested, I understand my rights, and I hereby consent to participate in this study.

____	______________________
Signature	**Date**

______ Initial here to permit photos and/or video from your assessment to be used for academic presentations and/or marketing purposes. These photos or videos will not show your face in any outlet in which they are used.

Appendix B – Data Collection Sheet

ID # ___________________

Demographics

Age: _______

Sex: ______

1. Are you an experienced female runner? Yes No
    a. If yes, approximately what is the average miles/week in last 6 months?____________
    b. How many years have you been running? ____
2. Are you able to complete a 5k race in 18-23 minutes or 10k race in 36-46 minutes? Yes No
3. Have you had a musculoskeletal injury that impacted running in the last 6 months? Yes No
4. Do you have a history of stress fracture(s)? Yes No
    a. If yes, when did your stress fracture occur? _________________
5. Are you familiar with treadmill running? Yes No
    a. If yes, approximately how much experience? ____________
6. Do you have any contraindications for exercise? Yes No

Anthropometrics

Height: ______cm

Mass:____kg

Shoe size: __________

Shoe Model:_________

Shoe mass: _________g

Preferred Running Speed: _______________

Initial Session

Trial Number	Running Speed (m/s)
1	
2	
3	
4	
5	

Biomechanical Variables (Overground trials)

Time	RPE
8:00	
9:00	
10:00	
Total distance completed:	

Physiological Variables (steady-state)

Training Session

Biomechanical Variables (Overground trials) Physiological Variables (Steady-state)

Trial Number	Running Speed (m/s)
1	
2	
3	
4	
5	

Time	RPE
8:00	
9:00	
10:00	
Total distance completed:	

Time (minutes)	Signal (Decibels)	Peak Decibel Signal	Average Decibel Signal
0			
3			
6			
9			
12			
15			

Auditory Signals (Steady-state run)

One Week Follow-up Session

Biomechanical Variables (Overground trials) Physiological Variables (Steady-state run)

Trial Number	Running Speed (m/s)
1	
2	
3	

4	
5	

Time	**RPE**
8:00	
9:00	
10:00	
Total distance completed:	