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Dose Response Relationship Between Aquatic Treadmill Running and Change to SI in Land Treadmill Running

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DOSE RESPONSE RELATIONSHIP BETWEEN AQUATIC TREADMILL RUNNIING AND CHANGE TO SI IN LAND TREADMILL RUNNING

By

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Introduction

Aquatic therapies have been used in some of the earliest human civilizations. Examples can be seen in China, ancient Rome and even in the early history of U.S. settlements.[1,2] Over the past few years aquatic environments have become a more common method for rehabilitation, injury prevention, and cross training. Additionally, research has observed that aquatic exercise may assist in pain relief, swelling reduction, and ease of movement due to the pressure and warmth of water.[7] Aquatic environments can also be used to reduce forces placed on the lower extremities by reducing the weight of the subject through buoyancy.[3] Buoyancy can unload a participant's body weight by as much as 70% when submerged to the xiphoid process.[4,30] Aquatic running has been shown to be an effective mode to maintain cardiovascular fitness and thus has potential to benefit runners as an alternative training method both in prevention and in the event of injury.[5] As evidence, Silvers, Rutledge, & Dolny observed that aquatic-treadmill running will elicit similar VO_2 responses when compared to land-treadmill running, making aquatic-treadmill running a viable cross training method.[6] However, previous research also observed once a subject is placed on an aquatic treadmill, there are changes that occur to both the kinetics and kinematic aspects of gait.[8,16,17,18,19,20] While many researchers have focused on the effects an aquatic environment has on the human body, little research has focused on aquatic-treadmill running and any carry over effect once the participant leaves the aquatic environment and returns to land-based running.

More than 35 million Americans are estimated to run for exercise.[13] With this many Americans running, there are bound to be injuries. One of the recent ways people are trying to avoid running-related injuries is changing the way their foot contacts the ground. One method to define how the foot contacts the ground is through a measurement known as the Strike Index

(SI). SI is an estimate of center of pressure (COP) on the dorsal surface of the foot during the stance phase of gait. Typically the COP, which is the theoretical point of application of the resultant ground reaction forces, is quantified using a force plate. SI is reported as a percent of the total foot length, with lower percentages (e.g. 0-33%) indicating a more posterior COP point of contact (e.g. rear foot strike), while greater percentages (e.g. 67-100%) indicate a more anterior point of contact (e.g. forefoot strike).[9] Recent research from our laboratory has observed that experienced runners exhibit a more forefoot strike pattern (SI ≈ 64%) during aquatic-treadmill running than land-treadmill running (SI ≈ 43%) at comparable speeds.[8] A more forefoot strike pattern has been reported to increase running economy,[10] reduce repetitive injury rates and decrease ground reaction forces.[11,12] A greater SI may also lead to adverse effects; research has suggested a more anterior strike may cause more Achilles tendon injuries[13] and a possible increased risk of metatarsal stress fractures.[14] Adjusting strike patterns may not be for all runners but for those looking to change their SI, the transition should be done with caution and over time.[14] There may be multiple methods to change one's SI; one method may be aquatic-treadmill exercise.

Training interventions such as resistance training, barefoot or minimalist running, or plyometric training have the potential to alter running mechanics through neuromuscular adaptations.[15] Aquatic treadmills are an example of an alternative training method for runners who want to alter one's SI during land running. What is not clear from research is how much aquatic-treadmill exercise is required to elicit a change in the SI during land-treadmill running. Research has established a dose response relationship between resistance training and neuromuscular adaptations. These responses may include increase cross sectional area of a muscle, increase number of motor unit innervation, frequency of motor unit innervation, and increased strength. Research has indicated that these neuromuscular adaptations occur at three bouts a week for novice and twice a week for more experienced individuals.[21,22,23,24]

Currently there is no dose response relationship established between aquatic-treadmill running and changes to SI in land running. An appreciation of the dose response relationship will help to maximize the training effect of aquatic-treadmill running. If this relationship is better understood, it will help to write prescriptions for aquatic-treadmill running for those interested in changing their SI during land running. Knowing the dose response relationship between aquatic-treadmill running and SI change to land-treadmill running may also give researchers an idea of how aquatic-treadmill running may affect other aspects of gait in healthy individuals. A dose response is established by introducing an intervention or treatment to a participant in a controlled setting. Once the intervention is added, the participant is observed for changes. In this study, the intervention will be aquatic-treadmill running while the SI during land-treadmill running will be the outcome measure. One approach to establishing a dose response relationship is to use a single subject research experimental design (SSED). Single subject experimental designs are ideal for establishing the viability of treatments before attempts are made at large scale group design studies.[27] Further SSED are critical for developing randomized control trials as they assess the feasibility and dose of a treatment and there specific individual effects.[27] The purpose of this study is to establish a dose response relationship between aquatic-treadmill running and the SI during land-treadmill running among healthy runners using an SSED.

Methods

This study will use a withdrawal SSED made up of three phases: A-Phase (baseline), B-Phase (intervention), and a second A-Phase (intervention withdrawal) (Table 1). A minimum of three phases is used to reduce threats to internal validity[40]. Repeated measures of the SI will be obtained at baseline to establish a clear pattern of stability over a minimum of three baseline data points with more being preferable.[27] Baseline data is used to describe current behaviors and predict future bhaviors[40]. Typically baseline is established through visual analysis. This research determined that baseline variability below 10% will be accepted based on pilot data values. Pilot data consisted of three participants tested three separate times. Tests were conducted at least 24 hours apart using the same methods as described later in the data collection section. Pilot data indicated that SI values stayed with in a 10% range during all pilot tests.

Participants will be recruited from Utah State University and the surrounding community. Inclusion criteria will be: 20-50 years of age, running at least 15 miles a week at time study begins, no current injuries that affect running performance or injuries in the past six months, no history of cardiovascular disease and are not currently engaged in an aquatic-treadmill exercise. A total of three Participants will be used, one from each age decade. All participants will provide written consent using methods approved by an institutional review board.

The A-Phase (Baseline) will be completed on a land treadmill (Freemotion Fitness, Logan, UT) at 0% incline which will match the incline of the water treadmill. The baseline phase will consist of a five-minute warmup, followed by running at a self-selected pace that is below aerobic threshold. The submaximal exertion will be verified using the 6-20 RPE rating scale. Target exertion levels will be between 11 and 15, which often correspond to 50-80% of VO_2 max.[28] Baseline data will be collected on three separate days with a minimum of 24 hours between collection days.

The B-Phase (intervention) will be conducted using a HydroWorx adjustable depth water treadmill (HydroWorx 2000, Middleton, PA). Participants will be submerged to the xiphoid process, which is a depth that elicits similar metabolic demands to land-treadmill running.[6] A five-minute warm up at a self-selected running speed will be performed; followed immediately by running at self-selected pace that will match the PRE rating acheived during Phase-A. Stride rates can decrease due to the buoyancy encountered while in water;[6] aquatic jets will be applied to participants while running to encourage stride rate patterns similar to land. On the basis of pilot data and the research of Silvers et al., the water jets will be set at 40% to encourage a more normal running gait pattern.[6] Participants will be asked to run for 20-min. Roper et al. observed that 20 minutes of exercise, three times a week on an aquatic treadmill may elicit neuromuscular changes to gait on land.[18] The 20 minutes in the water is broken down into four separate continuous 5 minute intervals. Minutes 1 - 5 participants will run at a self-selected pace as a warm up. Minutes 6 - 10 aquatic-treadmill speed will match on land treadmill speed selected during A phase with no jets applied. Minutes 11 – 15 40% jets will be applied and participants will select a speed that elicits the same RPE rating that was selected during A phase. The final 5 minutes will be a self-selected pace that will act a cool down for participants.

Immediately following completion of the aquatic-treadmill exercise, participants will be asked to run on the land treadmill. They will be given the opportunity to dry themselves, shower, and change back into dry clothes. The time between the aquatic-treadmill exercise and land running will not exceed 30 min as determined by pilot testing. The sequence of running on the aquatic treadmill followed by land treadmill running will be followed during all intervention trials. The post intervention land-treadmill running will be matched to the baseline phase (A) speed.

The A-Phase (intervention withdrawal) will be conducted following the end of B-Phase, which will be determined by a plateau in the SI or no change to SI after 6 weeks of intervention. The intervention withdrawal phase will be conducted the week following the completion of the intervention phase. The post intervention assessments will follow a protocol that is identical to baseline phase. The withdrawal phase will allow researchers to evaluate any lasting effects of the intervention. During all phases runners will be asked to “run as naturally as possible”.

During all three phases participants will be running in the exact same brand and model of shoe. During land trials participants will run the shoe they typically use for running. While participants run on the aquatic treadmill they will use a second pair of shoes that is identical to the land based running shoe. The second pair of shoes was provided to the participant by the researcher. The purpose for using two pairs of shoes is to allow the participant to have dry shoes to run in immediately following running on the aquatic-treadmill. Also running in shoes in the pool will increase the internal validity of the study by matching shoes worn during all phases. Participants were also asked to maintain their level of physical activity outside of the study throughout all three phases. Researchers commonly asked participants during data collection sessions about their physical activity to verify physical activity levels stayed consistent.

Data Analysis

Motion of the right foot will be collected between minute four and five of all land-treadmill trials during phases A, B and A. Foot motion data will be recorded using a Casio EX-F1 high-speed digital camera (Casio America Inc., Dover, NJ) with a sample frequency of 300Hz. The camera will be placed perpendicular to the lateral side of the right foot, at a distance of approximately 1.5 m from the edge of the treadmill deck and level with the horizontal plane of treadmill deck. Camera will be zoomed in to include just the foot when it contacts the treadmill deck; this is to maximize the image size and improve the foot strike angle (FSA) calculation. A minimum of five consecutive foot strikes will be used to quantify the FSA. Trials for phases A and B will be conducted three times a week with a minimum of 24 hours between trials to reduce effects of fatigue.[25] Measurement of FSA will be taken following each trial during phase B, maximizing the researcher's chance of finding the number of aquatic treadmill trials that will elicit a change to FSA. Roper et. al. found changes to kinematics in as little as three sessions on an aquatic treadmill.[20] Participants will perform all land and water trials in their own selected running shoes. A second pair of shoes will be provided to be used in water treadmill trials. The ability for participants to choose their own shoe may increase participants comfort; however, this should not affect the strike angle of the participant if they adapt a more anterior foot strike running pattern.[26]

To compute SI, FSA will be measured from the videos taken during land-treadmill running. To calculate FSA participants will have three reflective markers placed on the right side of the shoe, *figure 1*. Marker placement will be as follows: (A) lateral side of the calcaneus (level with the insertion site of the Achilles tendon), (B) The lateral head of the fifth metatarsal and (C) the lateral malleolus.[29] Once markers are placed participants, will be asked to stand on the land treadmill and a still photo will be taken of the right side of the marked shoe. This photo will be used to calculate $AB_{standing}$ as shown in *figure* 1. $AB_{footstrike}$ will be calculated as shown in *figure 2*. Angle measurements will be determined using the digital goniometer tool in Dartfish (Dartfish USA Inc., Alhparetta, GA). FSA will be computed as the difference between $AB_{footstrike}$ - $AB_{standing}$ using the convention as defined in *figures*. SI is then calculated using the FSA in the regression equation used by Altman, Davis[9], $\frac{(FSA-27.4)}{-0.39} = SI$. FSA is highly correlated with SI, R

= 0.92 (p <0.01), as found by Altman et a.l.[9] The average of five FSA computations will be used in the SI regression equation for statistical purposes.

Video analysis will be conducted by two trained motion analysis technicians using Dartfish software. Dartfish was chosen because it has been validated against 3D motion software in laboratory settings.[31] The primary technician will analyze 100% of video data using the Dartfish software and a secondary technician will analyze 30% of video data. The use of a secondary technician will have multiple benefits including; an increased value of interclass correlation coefficient (ICC), increased repeatability of results and minimize bias in the analysis of SI.

Videos of the intervention sessions were recorded using a GoPro Hero 3+ (GoPro Inc., San Mateo, CA) to verify that SI was different between land and treadmill trials. Camera was set on wide angle view with 720p resolution. Videos were taken between minutes 8 and 10 also between minutes 13 and 15. Camera was mounted to the pool wall roughly 1.5 M from the participant's right side and at a height that included the foot strike on the bottom of the pool.

Statistical Analysis

Analysis of data will be conducted in two ways; by visual analysis using time series plots as seen is *figure* 3 and statistical analysis. Visual analysis of plots will examine for changes in one or more of three parameters: level, trend (slope), and variability.[27] Level analysis consists of a distinct change in data points with average values in baseline having no overlap with the average in the treatment phase. Trend analysis identifies a visual change in slope between treatment and baseline. Finally, variability analysis is if the variability between data points is less in the treatment phase than in baseline data based on visual analysis. In SSED, determining experimental effects is based on visual inspection as the primary mode of analysis, with statistical analysis as a supplement to the visual analysis[40].

Statistical analysis will be done to provide support to the visual analysis. A piece-wise regression using the number of training sessions as the predictor variable and SI as the response variable will be the first step in the statistical analysis. The piece-wise formula is applied iteratively; estimating the change point in the data using a defined metric (minimizing mean standard error). This regression analysis is favored over the synonymous regression-discontinuity approach because it objectively defines the change point in the data. If the regression is significant we can predict the number of training sessions in the pool needed to elicit a change to SI on land and also predict the magnitude of SI change using trend analysis. Knowing the number of sessions that it takes to elicit a change will allow researchers to establish the dose-response relationship. 95% confidence intervals will be computed for the change point using Jacknife resampling. All hypothesis testing will be performed using an alpha level of 0.05.

To ensure inter-rater reliability of marker placement and initail contact estimation, the ICC will be calculated by comparing the average five consecutive FSA in 15 separate videos. Videos will be chosen at random between participants and phases.

Results

Three participants, two female and one male were included in the study. Participant 1 was a 24 year old male, with a height of 1.87m and a mass of 83.8 kg. Participant 2 was a 37 year old female; height and mass were 1.72m, 62.3 kg. Participant 3 was a 40 year old female, 1.67m height with a mass of 51.3 kg. Mean age (SD) age was 33.7 (8.5), mean (SD) height was 1.7m (0.1), and mean (SD) weight was 65.9 Kg (16.5). All three participants completed 18 sessions of aquatic treadmill running during the six week intervention phase.

Visual analysis of SI values between-phase comparisons identified no change in trend or level. Variability between A-phase (baseline) and B-phase (intervention) had the largest change. All participants showed increased variability between baseline and intervention phases, with variability during A-phase (withdrawal) returning to values closer to baseline. Visual analysis suggested participant 1 had the greatest increase in variability once the B-phase began and maintained that level of variability throughout (Figure 3). Participant 2 showed large amounts of variability through the first six B-phase trials. Trials seven through 18 had a slight decrease in variability (Figure 4). Participant 3 was the only participant who showed any visible change in level, and a decrease in variability, with the change beginning after eight intervention sessions (Figure 5).

Statistical analysis for participants 1 and 2 showed no statistical significance for trend. Using the piece-wise regression participant 3 showed a statistical significance, $R^2 = .504$, ($p = .001$), with a positive increase in SI of .784 per aquatic treadmill session and $F = 16.3$, ($p = .001$). Basic statistical analysis of mean and standard deviation did verify the changes in variability found through visual analysis. Participant 1 mean (SD) for baseline, intervention and withdrawal was; 32 (3), 32 (6.4), 35.7 (2.6) respectively. Participant 2 showed similar changes in mean (SD) through all three phases; 24.3 (2.4), 22.5 (4), and 23.6 (2.1). The change in standard deviation between phases was the largest in s participant 3 with baseline phase mean (SD) 31.5 (1.3), intervention phase mean (SD) 27.2 (5.9) and withdrawal phase mean (SD) 34.2 (0.6).

Using the 15 videos analyzed by the secondary technician and compared with the primary technician an ICC value was calculated using Microsoft SPSS statistical software, ICC = .934 ($p < .001$).

Discussion

Based on the visual and statistical analysis of the data, we have failed to establish a dose response relationship between aquatic-treadmill exercise sessions and change in SI when the participant is returned to land-treadmill running. No clear pattern or systematic change to SI was established in any of the participants. An increase in variability during the intervention phase was observed throughout all participants. Each participant had different levels of variability, but all participants revealed an increase between baseline phase and intervention phase. The increase in variably may be due to the fatigue of the tibialis anterior muscle. When participants are placed on an aquatic-treadmill one of the most noticeable differences to the runner is the increased work load placed on the tibialis anterior. All three participants may vocal comments about being able to immediately feel the difference. The muscle is activated more in the water than in land-treadmill running to keep the foot in a dorsiflexed position while the leg is swung forward during the swing phase of gait[18]. The added resistance is caused by the increased fluid drag that the water exerts on the foot[18]. Variability of SI in the withdrawal phase returns to values close to those found in the first baseline phase. This may lend support that that tibilais anterior fatigue may not be controlling dorsiflexion as well after participants have been on the aquatic-treadmill. Research conducted by Christina et. al. examined the effects of localized fatigue of the tibialis anterior and its effects on foot angle and GRF during running. Their research found that when a muscle is responsible for acting eccentrically just after heel strike, a localized fatigue state may inhibit the ability of the muscle to contract concentrically to achieve a “desired” joint angle at touchdown[42]. The results found by Christina et. al. also showed an increase in standard deviation among the foot angle at initial heel contact during running. EMG research has shown that even during land based running the tibialis anterior muscle is active during 50 – 85% of the running cycle and has a high probability of fatigue.

Participants were recreational runners who ran a minimum of 15 miles per week. This criteria lead researcher to believe that all three participants had a stable motor program for the activity of running. A stable motor program can be defined as; a same sequence of activation components[35]. Ivanenko et. al. suggests that the motor program for walking and running is basically unaltered due to change in speed[35]. The six week intervention may not have been enough to break down this motor program and allow the participant to learn a new program or to change the current motor program. Researchers based the six week program off past literature that states a neuromuscular change can occur in exercise programs in as little as six weeks[21,37,38]. Research by Turner et. al found 6 weeks of plyometric training among non-lite runners improved running economy. The 6 weeks training schedule used by Turner et. al. included only three sessions per week and observed changes among runners economy.

Proprioception is the sensory feedback that contributes to conscious sensation segmental posture or joint position[32]. Previous research suggests that running barefoot may increase proprioception in the foot and ankle[33]. Our participants wore shoes while running on the aquatic-treadmill to match running styles between land and water. This was done to reduce external influences on running style while on the aquatic treadmill. This may have lowered the participant's ability to sense ankle angle while in the water and reduce the effect that the aquatic-treadmill had on the SI of the participant. Research has shown that sole thickness can have an effect on perception of joint position. Both thin soled and thick soled shoes can decrease an individual's ability estimate the amount of dorsiflexion, plantar flexion, inversion and eversion when the foot position is manipulated using sloped blocks[39].

While we did not establish a dose response relationship with aquatic-treadmill running and a change to SI, we did observe an increase in trial to trail variability during the intervention phase. Participant 1 had an increase in standard deviation from 3 to 6.4 between baseline and intervention phase. Participant 2 showed similar increases of 2.4 to 4. While participant 3 had the largest difference in standard deviation between baseline and intervention phase with vales of 1.3 in baseline and 5.9 in intervention. An increase in variability in SI may be a benefit to habitually shod and rear-foot striking runners. One of the biggest causes of injuries to runners is repetitive motion. Striking the ground in the same way ever time increases these risks. Overuse injuries in athletes are generally due to overload or repetitive microtrauma of the musculoskeletal system. Most overuse injuries are associated with events including running or jumping[41]. If you can introduce some variability into how the ground is contacted during running you may be able to slightly lessen repetitive contact injuries. Even if the change is not drastic moving the SI will change the direction and magnitude of forces applied to the body[34]. To the researches knowledge an increase in SI variability is not detrimental to running performance.

Running on an aquatic treadmill may have many benefits to runners, independent to the outcome measure used in this study. While in the water runners will experience lower forces exerted on the body[3], reduction of pain and swelling[7], and can achieve similar cardiovascular training effects[5]. Even if there is no change to SI when the participant engages in aquatic-treadmill exercise program they are still gaining the other benefits that have been associated with aquatic- treadmills. The researchers believe that changes to participant’s gait may have occurred, such as; knee angle at contact, increased stride rate, decreased stride length, or over knee angle. However, these measures were outside the scope of the current study.

All participants made verbal comments through the intervention phase expressing how they enjoyed running in the water. Participant 3 was the most vocal and on multiple occasions expressed her like for the aquatic-treadmill. Some of the comments included; “The underwater treadmill is relaxing to run on”, “I feel like the muscle on the front of my leg (pointed out the location of the Tibialis Anterior muscle) is getting stronger.” Participant 1 also made comments about the leg muscles feeling stronger after the 6 weeks of intervention phase. These comments led the researcher to believe that the aquatic-treadmill can be an effective cross training and a method that is enjoyable to runners.

Limitations to or research may be related to time intervention was applied. We may have seen changes if intervention phase was applied to participants longer. Also limited baseline data may have contributed to lack of statistical significance in data. Similar research analyzing changes in foot strike patterns have seen changes in 8 weeks when using a minimalist shoe as the training tool[35]. Also runners were allowed to participate in their regular workout routines outside of the study, this continued running on land may have saturated any affects from the aquatic-treadmill.

The information gained in this research may not have established a clear dose response relationship, it has however given insight into some of the changes happening to SI when runners use aquatic-treadmills as a cross training method. Running in an aquatic environment has many benefits such as; pain and swelling reduction, injury prevention and rehabilitation and reduced GRF forces. A change to SI in land based running may not be one of those benefits, so for a runner looking for viable cross training environment an aquatic-treadmill may be for you. If you are a runner looking to change your SI during land based running, aquatic-treadmill running may not be the best method to change SI. Additional research may be needed to identify other changes occurring to the kinematics of land running after using an aquatic-treadmill and to identify the effects of longer training periods.

Methods flow chart

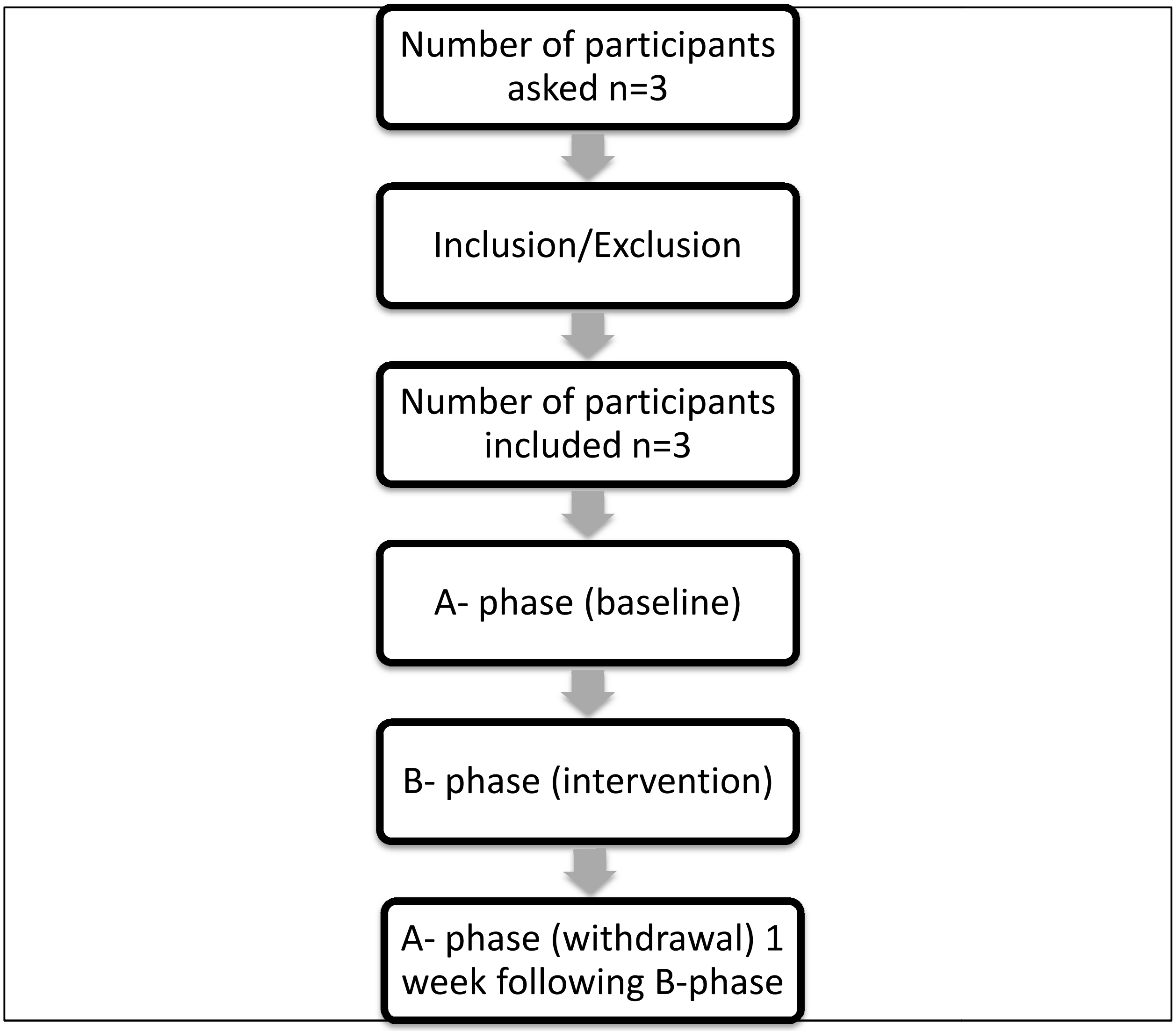

Table 1. Outlining selction of participants and the order of different phases.

Figure 1. $AB_{standing}$ angle as discussed in the data analysis section.

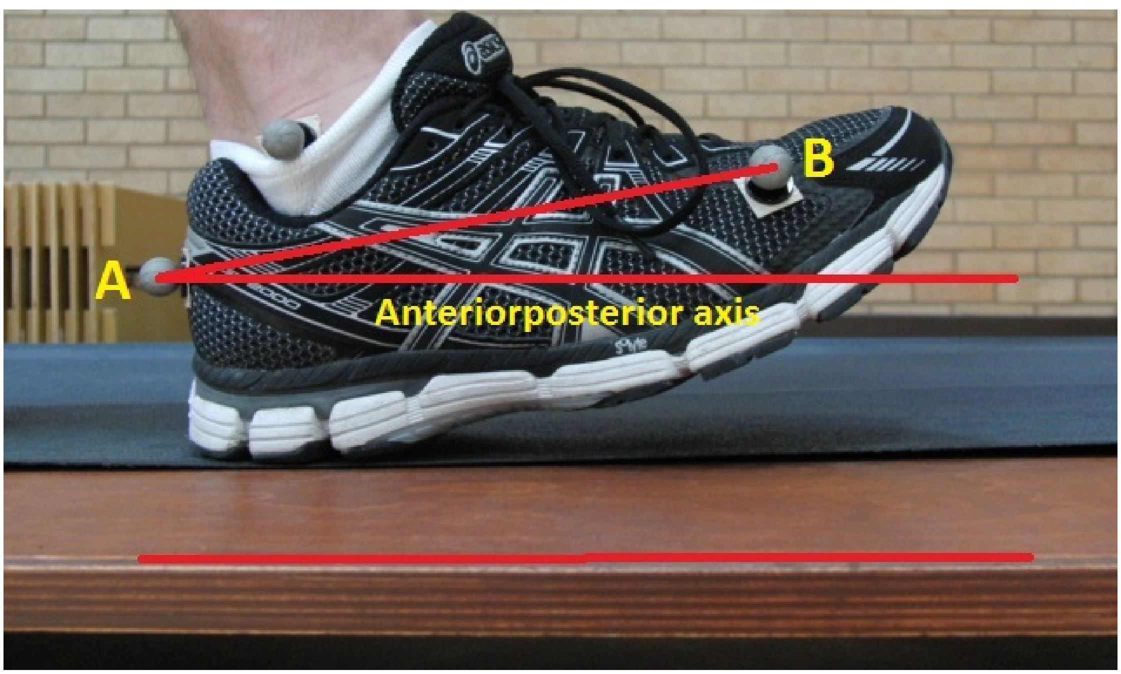

Figure 2. $AB_{footstrike}$ angle as discussed in the data analysis section. FSA is calculated as the difference between using the equation $AB_{footstrike} – AB_{standing} = FSA$

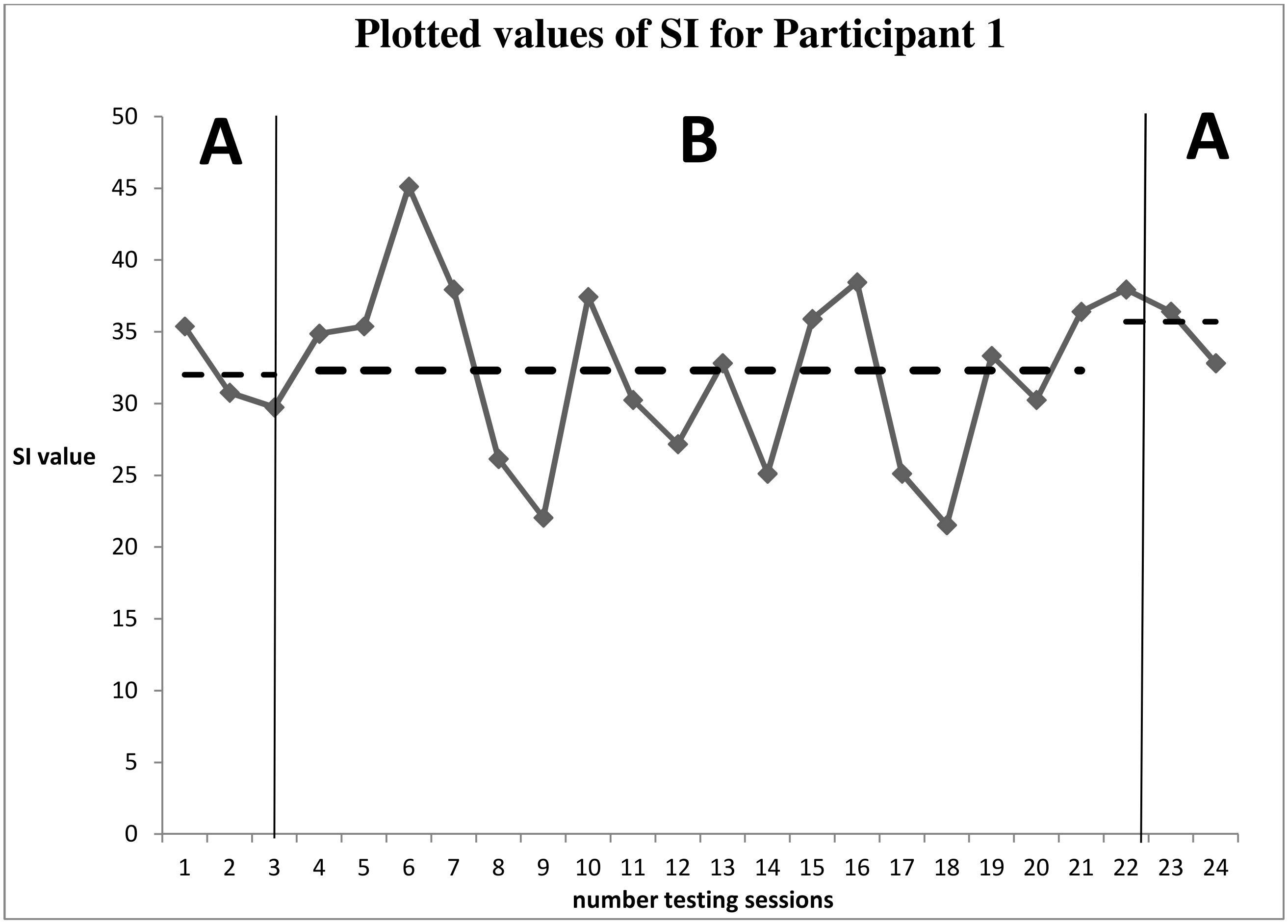

Figure 3. Plotted SI values for participant 1, showing increase in variability throughout the intervention phase. Graph also shows little to no change in mean value between baseline and intervention. Mean values shown with straight line through phase.

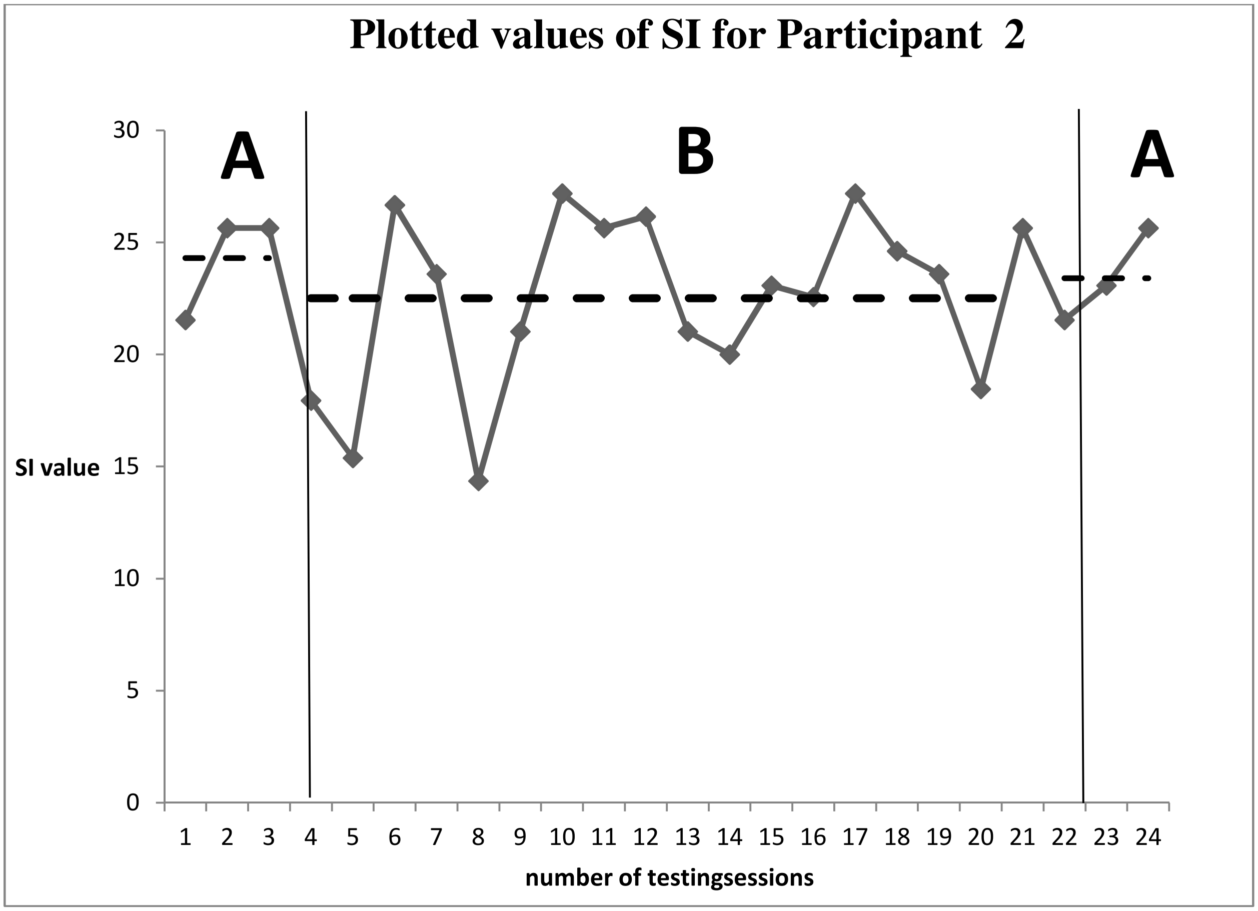

Figure 4. Plotted SI values for participant 2, showing increase in variably through the first six intervention trials with a decrease through trials 7 – 18. Mean values shown with straight line through phases.

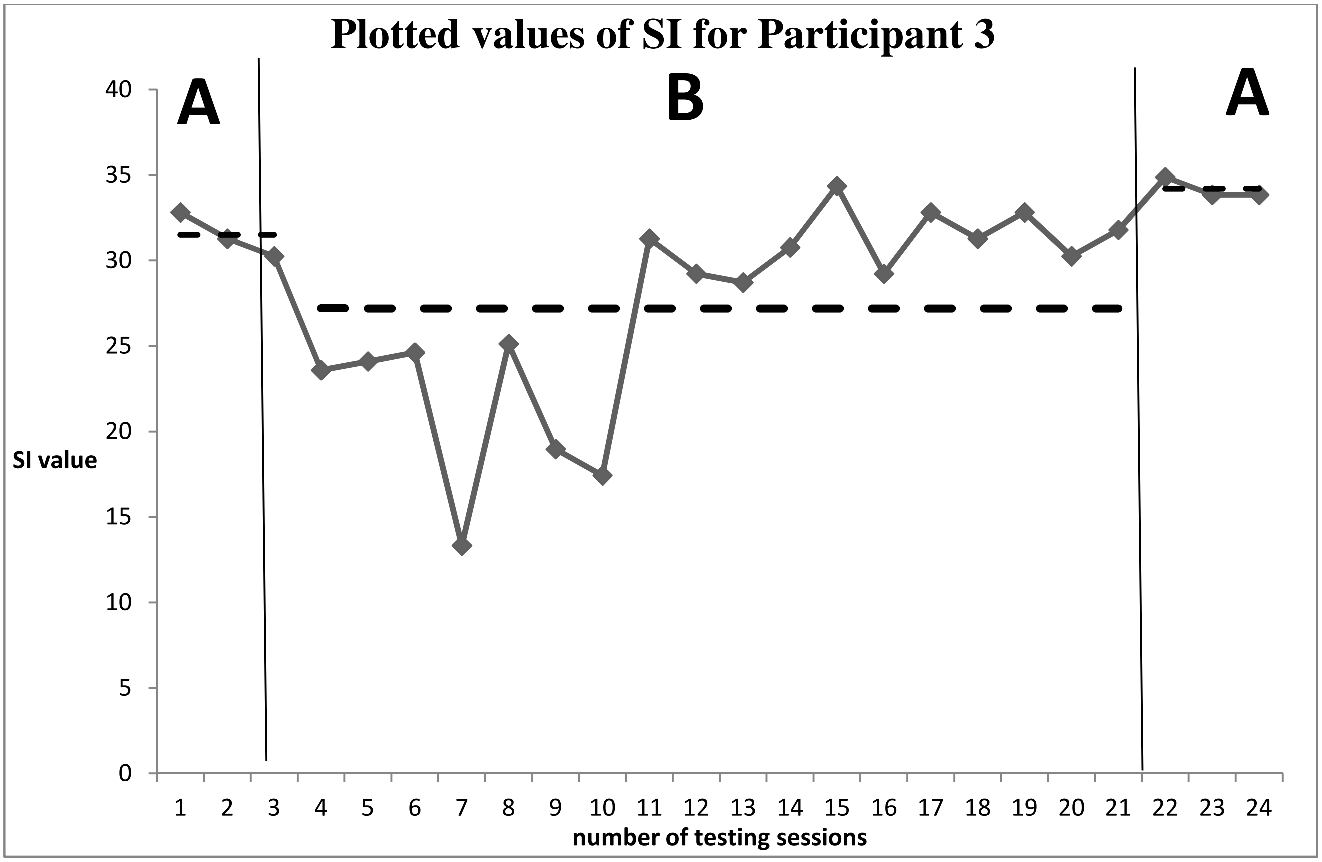

Figure 5. Plotted values of SI values for participant 3, showing a possible change in levels at session 12 and a decrease in variability. Mean values shown with dotted line through each phase.

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