Treading Lightly: The Effects of Textured Insoles on

Postural Control and Locomotor Adaptation

by

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ABSTRACT

The current program of work explores the potential efficacy of textured insoles for improving biomechanical performance and cognitive acuity during static and dynamic performance. Despite the vast conceptual framework supporting the versatile benefits of textured insoles, the current literature has primarily focused on incorporating this treatment during low-phase movements within the diseased and elderly subset populations. The current study expands this research application by administering textured insole treatments to a healthy population during a physically demanding dynamic assessment and correlating the results to subjects' sensory perception. A convenience sample of 10 subjects was evaluated for their ability to maintain bilateral standing balance in a static condition and adapt to confined lane perturbations during standard track running. These evaluations were conducted under both control and textured insole conditions. Subjects also completed a visual analog scale test, rating the insole treatments based on surface roughness to establish a statistical relationship between individual perception and biomechanical performance. Results showed that textured insole treatments given intermediate ratings of perceived surface roughness significantly enhanced performance during bilateral standing balance and standard track running perturbation adaptation.

I would like to extend my sincerest gratitude to my family. I have been fortunate enough to have parents who have worked tirelessly to provide me with every opportunity imaginable and a brother that has supported me every step of the way. Thanks Mom, Dad, and Jim.

And to my dog, Pid.

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These acknowledgements would not be complete without also thanking the other half of my thesis member committee and principal investigator of ASU's Neural Control of Movement Laboratory, Dr. Marco Santello. Dr. Santello has graciously taken it upon himself to accept me into his academic unit for the duration of my final semester here at ASU, and I am actively looking forward to hearing what he and his lab achieve next.

A special thanks to my primary thesis advisor, Director of the ASU Center for Engagement Science and close friend, Dr. Aurel Coza. Over this past year, Aurel has influenced my career in an indescribable fashion by introducing me to a path forward in professional research. He has afforded me the opportunity to work independently as a leader on my final culminating experience, and I cannot thank him enough for his diligent mentorship and knowledgeable oversight throughout this project.

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LIST OF ABBREVIATIONS

CNS	Central Nervous System
ASU	Arizona State University
PARQ	Physical Activity Readiness Questionnaire
VAST	Visual-Analog Scale Test
BAST	Balance and Stability Test
DTA	Dual-Task Assessment
DAST	Dynamic Auditory Stroop Test
DALT	Dynamic Adjusted Lane Test
I1	Insole 1
I2	Insole 2
I3	Insole 3
I4	Insole 4
VAS	Visual Analog Scale
VST	Visual Stroop Test
%ΔV	Percent Change in Velocity
V1	Velocity1
V2	Velocity2
GRMS	Root Mean Squared Acceleration
DAF	Directed Attentional Focus
fMRI	Functional Magnetic Resonance Imaging
EEG	Electroencephalography
MEG	Magnetoencephalography

CHAPTER 1

INTRODUCTION

1.1 Application and Relevance

The sports optimization industry represents a vast domain of scientific research that encapsulates the comprehensive analysis of every external and internal factor that could potentially influence overall human performance (Mfaba, 2022). Examples of such external factors affecting sporting proficiency could be environmental, taking the form of changes in weather or playing surface. On the other hand, internal influences such as physical fitness and emotional state are equally as impactful (Kopp & Jekauc, 2018; Tur-Porcar & Ribeiro-Soriano, 2020). However, addressing a single one of these factors would not be a sufficient technique for properly optimizing performance. Instead, successful methods typically leverage the complex interplay of all of these factors in order to achieve complete and consistent results through a comprehensive ecological approach to the matter (Davids et al., 2013; Vilar et al., 2012).

An excellent example of this phenomenon can be seen in the expansive industry presence occupied by novel products seeking to provide athletes with a competitive edge via evidence-based equipment modifications. Athletic equipment takes the line between internal and external performative influences and jumps rope with it. Skill-promoting (and inhibiting) sports products are able to have profound effects on the level of performance an individual is able to achieve because an athlete's internal cognition is heavily influenced by any functional modification to their environmental perception (Araújo et al., 2006; Taylor et al., 2016). These principles can be easily viewed through a thorough analysis of the footwear innovation space.

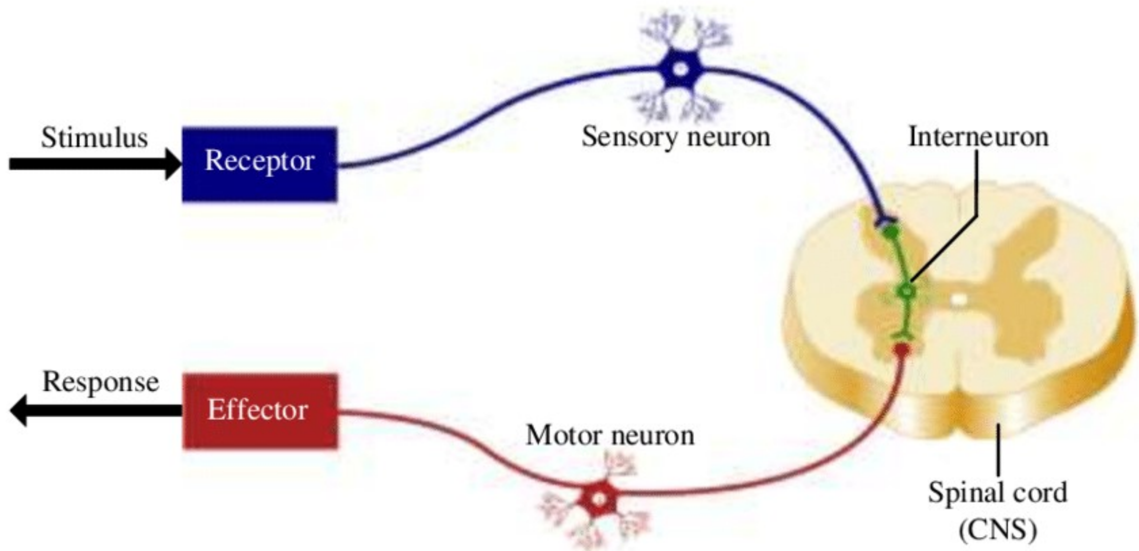

Figure 1. *Visual depiction of the interconnected sensory components responsible for processing external stimuli through the central nervous system (CNS). The reflex arc provides a streamlined neural pathway, with minimal elapsed time from perception to response needed during motor adjustments. This stimulus-action loop consistently modulates fine motor movements to maintain postural homeostasis* (Li et al., 2014).

Footwear directly interfaces an athlete's sensory perception with the playing surface (Kavounoudias et al., 1999; Viseux, 2020). Communication between these two dependent entities represents a coupling of perception and action that is critical for completing necessary tasks in response to different stimuli (Fajen et al., 2009; Seifert et al., 2013). The phenomenon describing the interaction between the foot and the surface on which it rests represents a stimulus-action feedback loop (Figure 1) that is constantly cycled to achieve postural homeostasis (Orth et al., 2013; Wu & Chiang, 1997).

Although the playing surface is usually standardized in a competition setting, new product development initiatives have been able to take advantage of the foot's sensory capabilities through footwear adjustments that impact the inner surface of the shoe rather than the external surface of play in hopes of improving performance. This type of intervention could potentially facilitate processing of the stimulus-action feedback loop, resulting in more efficiently organized and learned movements (Aries et al., 2022; Friehs et al., 2022; Robb & Perry, 2022).

1.2 The Foot as a Sensory Structure

1.2.1 Overview

Many of the mechanisms involved in enhancing complex actions through footwear optimization are largely unknown. However, a clearer picture of this psychophysical interaction can be inferred from a more in-depth understanding of how the foot functions as a critical sensory organ during both casual and athletic endeavors. The aforementioned stimulus-action feedback loop that allows for maintained postural control, functions through a cooperation between the somatosensory system (responsible for stimulus detection) and the motor system (responsible for action or movement response) (Deliagina et al., 2006; Viseux, 2020). In essence, the somatosensory system acquires both tactile and proprioceptive feedback from the foot-ground contact experience, and the motor system integrates this sensory information through the central nervous system (CNS) in order to facilitate corresponding biomechanical adjustments (Alfuth, 2017; McGlone & Reilly, 2010).

Now that the stimulus-action feedback loop and its internal communicative process from sensory signal to motor response is understood, the focus of this mechanism can be further explored by defining how the somatosensory system perceives the external stimulus in the first place. The stimulus detection of plantar inputs is typically carried out by sensory afferents located in either the skin of the foot or the skeletal muscles innervating the general foot area (Kavounoudias et al., 1999; Kennedy & Inglis, 2002; Viseux, 2020). The primary sensory afferents involved in these processes are cutaneous receptors (found in the skin) and muscle spindle endings (found in surrounding skeletal muscles), respectively (Viseux, 2020). Both receptor categories are essential for providing sensory feedback to the CNS in order to respond to the continuously changing experience of the foot perceived through foot-ground interactions (G. Macefield et al., 1989; Viseux, 2020).

1.2.2 Cutaneous Mechanoreceptors

Specialized afferent receptors, known as cutaneous mechanoreceptors, are responsible for registering perceived tactile stimuli resulting from deformation of the glabrous skin and hairy skin regions of the foot (Johnson, 2001; Kennedy & Inglis, 2002; Nurse et al., 2005). Supporting the body during environmental interaction induces varying levels of pressure, skin stretch, and vibration, which lead to the experienced sensation of mechanical skin deformation within plantar regions (V. G. Macefield, 2021; Mildren & Bent, 2016; Strzalkowski et al., 2018). Due to the ever-changing contrast in mechanical stimuli presented to the different sensory areas of the foot, cutaneous mechanoreceptors are constantly at work updating the CNS to coordinate appropriate motor responses necessary to maintain homeostasis in the stimulus-action feedback loop (Hennig & Sterzing, 2009; Kavounoudias et al., 1999; Kennedy & Inglis, 2002).

The smooth skin on the foot sole, known as the glabrous skin, is heavily lined with cutaneous mechanoreceptors (Hennig & Sterzing, 2009; Katic et al., 2022; Kennedy & Inglis, 2002). The level of stimulation perceived by the cutaneous mechanoreceptors on the foot sole correlates to the amount of sensory feedback transmitted to the CNS (McGlone & Reilly, 2010; Tortolero et al., 2008; Viseux, 2020). These specialized sensory afferents lining the bottom of the foot have been shown to provide feedback on tactile stimuli due to mechanical perturbations (Maki et al., 1999; Sklar & Sarter, 1999).

The biomechanical properties of the cutaneous mechanoreceptors and the skin in which they reside directly reflect the foot's ability to signal the presence of mechanical stimuli through membrane depolarization and action potential generation (Peters et al., 2016; Viseux, 2020). The CNS's ability to continuously communicate with the foot's sensory system through action potentials ultimately translates into an individual's capacity for dynamically regulating postural control (Hennig & Sterzing, 2009; Kennedy & Inglis, 2002; Peters et al., 2016).

1.2.3 Muscle Spindle Endings

Although the perception of mechanical stimuli via cutaneous mechanoreceptors is essential to the body's somatosensory response, it only provides half of the compelling narrative underlying the foot's holistic experience of environmental interaction. The other half of this captivating tale is told primarily by proprioceptive afferent receptors, known as muscle spindle endings. Muscle spindle endings are a complex combination of intrafusal muscle fibers wrapped in sensory nerve endings (V. G. Macefield & Knellwolf, 2018). These specialized sensory structures are found in the fleshy parts of skeletal muscles innervating the plantar surface and are mainly responsible for mediating proprioceptive awareness (the body's positional awareness in space relative to its base of support) (V. G. Macefield & Knellwolf, 2018; Proske & Gandevia, 2012; Viseux, 2020).

Unlike cutaneous mechanoreceptors that detect skin deformation, muscle spindle endings are primarily responsible for providing proprioceptive feedback on muscle deformation (Knellwolf et al., 2019; V. G. Macefield & Knellwolf, 2018). Muscle deformation is a natural process involved in movement control. It can be observed through the perception of the angular position of different body segments, which dynamically varies with respect to muscle lengthening and shortening velocities (V. G. Macefield & Knellwolf, 2018; Proske & Gandevia, 2012). Sensations perceived by muscle spindle endings in the form of muscle stretch are also integrated within the CNS via the facilitation of ion-channel openings and action potential transmission (Knellwolf et al., 2019; Severini et al., 2023).

1.2.4 Sensory Afferent Coprocessing

Cutaneous mechanoreceptors and muscle spindle endings are primarily involved in the continuous regulation of postural control in response to tactile and proprioceptive stimuli, respectively. However, it has been postulated that these perceptual structures are also part of a more nuanced cooperation that involves the coprocessing of all signal information in order to generate a cohesive report on the body's sensory experience (Aimonetti et al., 2012; Maurer et al., 2001; Roll et al., 2002). For example, joint movements that may occur during natural gait have also been shown to induce varying degrees of skin stretch. While the body's muscle spindle endings register the proprioceptive feedback from the joint movement, cutaneous mechanoreceptors are also employed to report on the sensation of skin stretch.

It has been suggested that these signals, although perceived as separate plantar inputs through differing afferent structures, are integrated within the CNS, thus providing a holistic perception of the body's somatosensory experiences (Aimonetti et al., 2012; Kavounoudias et al., 2001). This specific mechanism describing the coprocessing of mechanical and proprioceptive feedback is yet to be confirmed; however, a cross-modal model of stimuli detection has been observed as mechanoreceptors do appear to play a role in providing proprioceptive feedback (V. G. Macefield, 2021; Mildren & Bent, 2016; Purves et al., 2001).

Recent studies have also shown that mechanoreceptors, although previously thought to carry out specialized somatosensory responses, actually function as part of a more cohesive union by integrating sensory inputs from different receptor types within the CNS through common afferent pathways (Kim et al., 2020; Kuroki et al., 2017; Saal & Bensmaia, 2014). Therefore, cutaneous mechanoreceptors may provide proprioceptive feedback either through the coprocessing of signal information with proprioceptive muscle spindle endings or via their own sensory capabilities (Aimonetti et al., 2012; Purves et al., 2001). Either way, stimulation of the foot sole has been shown to significantly increase both tactile and proprioceptive feedback, resulting in proportional increases in biomechanical performance (Dhruv et al., 2002; Waddington & Adams, 2000, 2003; Zehr et al., 2014).

1.3 Sensory Augmentation Devices

With this explanation of the generalities involving the underlying mechanisms of the foot's sensory experience viewed through the perspective of the stimulus-action loop, focus can now be returned to leveraging this information for performance optimization in the footwear innovation space. It has been established that a prominent component of the foot-shoe interaction is the foot sole-insole connection. Essentially, the root of perceptive initiation in the foot is funneled through the foot sole, making the insole of the shoe a critical feature for the communication of sensory feedback (Alaee et al., 2022; Strzalkowski et al., 2018).

Various techniques have been developed that effectively enhance cutaneous feedback through the incorporation of additional sensory stimulation delivered to the foot sole. Many studies have linked these increases in plantar cutaneous feedback to improvements in biomechanical and proprioceptive parameters (Collins et al., 2003; Lipsitz et al., 2015; Severini et al., 2023; Waddington & Adams, 2000, 2003). Increasing stimulation to the plantar regions to enhance balance, gait stability, and other biomechanical measures can be achieved with the help of sensory augmentation devices (Shull & Damian, 2015; Strzalkowski et al., 2018). A focal point of research done on plantar cutaneous augmentation has targeted the sensory experience of the foot sole through sensory augmentation devices implemented within shoe insoles (Lipsitz et al., 2015; Miranda et al., 2016; Priplata et al., 2003). This method allows for a direct contact point between the stimulation device and the cutaneous mechanoreceptors on the bottom of the foot.

An interesting caveat to plantar cutaneous augmentation is that the current scientific literature suggests it to be a cross-modal phenomenon, at least at the subthreshold level (Collins et al., 2003). This means the foot sole's sensory thresholds can be lowered through additional stimulation delivered by different input signal mediums. For example, cutaneous augmentation studies have shown enhanced feedback resulting from the addition of tactile stimuli, vibrational stimuli, and even non-noxious electrical stimuli (Corbin et al., 2007; Dhruv et al., 2002; Mildren & Bent, 2016; Zehr et al., 2014).

Although fascinating, the incorporation of actively regulating insoles requiring a constant power supply is impractical for daily use and would most certainly be deemed unacceptable within the regulatory constraints of athletic competition. Therefore, it can be concluded that the shoe insole technology domain could most directly benefit from cutaneous augmentation through the addition of tactile stimuli, which is a proven method for passively increasing foot sensitivity through materials that are inexpensive and easy to manufacture (Hasan et al., 2016; Sklar & Sarter, 1999).

1.4 Textured Insoles

A specifically promising application of the tactile flavor of cutaneous augmentation can be seen in textured insoles. Like other mechanical methods for enhancing cutaneous sensitivity, textured insoles have the ability to increase the stimuli perceived by the glabrous skin on the foot sole through induced skin deformation (Alfuth, 2017; Nurse et al., 2005). In this case, skin deformation occurs due to the application of a tactile pattern, typically comprised of protruding nodules of varying spatial distributions printed onto the shoe insole in some fashion. Although the textured pattern tends to vary across different studies (i.e., altering levels of texture nodule height, width, and spacing), a general effect has been observed when employing the technology across all populations throughout multiple spectrums of activity (Christovão et al., 2013; Kenny et al., 2019).

Research efforts to assess the efficacy of textured insoles have mainly focused on their application within diseased populations, specifically those suffering from conditions resulting in diminished perceptual capabilities, such as peripheral neuropathy (Alaee et al., 2022; Dixon et al., 2014; Hatton et al., 2019, 2023). Textured insole treatments within these groups have been shown to be effective in improving static balance, proprioception, and various gait parameters (Aruin & Kanekar, 2013; Palluel et al., 2008; Perry et al., 2008). Textured surfaces have also been shown to induce a similar impact on healthy populations through multiple studies that demonstrate health-promoting effects on postural stability during static and dynamic tasks (Aruin & Kanekar, 2013; Corbin et al., 2007; Nurse et al., 2005; Robb & Perry, 2022).

However, studies involving the application of textured insoles in athletic populations are few and far between. Although limited, certain studies have shown that textured insoles are an effective method for improving lower limb kinematics and proprioception in athletic populations (Bapirzadeh et al., 2014; Hasan et al., 2016; Waddington & Adams, 2000, 2003). Even scarcer are studies that show the performative benefits of textured insoles in dynamic sports-related tasks; however, these studies do exist in small numbers within the current literature (Hasan et al., 2016; Miranda et al., 2016).

1.5 Specific Aims

Although a vast amount of evidence exists to support the performance-promoting effects of textured insoles, this research domain suffers from a few shortcomings. Primarily, the directed focus of textured insole interventions in the elderly and diseased populations could be slightly misguided or, at the very least, unreasonably exclusive to those populations as young and healthy populations could potentially experience more significant benefits from cutaneous augmentation by virtue of inherently lower sensory thresholds (Perry, 2006; Peters et al., 2016).

It has also been suggested that experienced athletes are better able to incorporate and process the addition of sensory information, leading them to experience more considerable overall performance improvements compared to novice participants (Hasan et al., 2016). Focusing the research of textured materials on diseased and elderly populations has also largely limited studies to the analysis of static and low-phase movements, resulting in a significant lack of studies into physically demanding dynamic actions such as those seen in sport-specific training and exercise regimens.

Another missing piece in the study of textured surfaces is the lack of definitive evidence regarding the underlying mechanisms responsible for their cognitive effect. Although previous studies have produced evidence that textured insoles have an effect, very few have shown or postulated why this effect occurs. Defining a mechanism that relates an individual's perceptual experience to their performative output would provide a constrained set of footwear development recommendations describing the criteria for effective tactile formations.

This information would be invaluable for translating textured materials into a novel category of sports performance products. Without a clear understanding of how textured insoles improve performance on a cognitive level, any prototype employing this technology would be speculative at best. An evidence-based model of textured insoles would ideally incorporate a previously established relationship between the perception of texture and corresponding locomotor effects.

The current program of work aims to produce a research output that addresses all the aforementioned loose ends regarding the analysis of textured insoles. First, a subject population will be recruited free of any conditions or disorders altering the individual's ability to carry out physically demanding goal-directed movements. This constraint will exclude all subjects with any current impairments that could prevent them from completing the assigned tasks or perceiving the effects of the experimental interventions. The current study will, therefore, be able to provide a unique analysis of the effects of textured perception on a healthy sample. The results of such an analysis shed light on how those outside of the diseased and elderly populations incorporate additional sensory feedback delivered by textured materials. By eliminating confounding sensory factors and constraining the study population to young, healthy individuals, a clearer tapestry of evidence-based recommendations will emerge that can be more directly translated into the realm of athletic competition.

The intentionally recruited sample for this study will also expand the literature on textured insoles by providing data on dynamic, fast-paced actions. Whereas previous studies have focused heavily on static manipulation, the current study's subsequently outlined methodology for assessing locomotor adaptation during standard lane running significantly expands the current knowledge on how physically demanding tasks are carried out under a textured insole intervention. When considering the potential for sensory augmentation devices within the industry of sports optimization, data in this domain would be of much higher relevance than studies revealing relative effects during low-phase movements. Analyzing the effects of textured insoles on dynamic postural regulation will also indicate whether such an intervention is still effective when coupled with the additional vibratory stimulus resulting from ground impact during the foot loading and unloading phases of running.

Most importantly, the current study attempts to establish a cause-and-effect relationship between perceptual affordances and sensorimotor performance. Static and dynamic tests of postural control will be administered to assess how each subject is able to maintain balance and adapt to gait-modifying perturbations. The subject repeated these tests while instrumented with various models of insoles containing differing textured surface designs. However, before completing the static and dynamic biomechanical assessments, subjects were instructed to complete a cognitive assessment, requiring them to rank perceived levels of surface roughness under each insole condition. With these data points, a correlation was constructed relating the perceived surface roughness experienced by each subject to their biomechanical performance on the assigned tasks. This relationship, correlating cognitive and perceptual experience with performance provides clear and constrained footwear development guidelines for the efficient translation of textured insole research into a validated sector of industry products. The current study endeavors to model this mechanism while providing novel insights into the lightly explored effects of textured insoles during physically demanding tasks within young, disease-free populations.

CHAPTER 2

METHODS

2.1 Participants

Subject interest was initially gauged through word of mouth, as the primary investigators directly approached members of the general student body at Arizona State University (ASU) and residents of the broader Arizona population. Potential subjects were asked if they were interested in participating in a study at ASU that aimed to gain perceptual and performance-based feedback on various proposed footwear constructions. At this time, additional information regarding the specific tasks involved in experimentation and any other requirements to be fulfilled before attending the testing facility were also provided.

Interested parties indicated their willingness to participate by providing complete contact information, consenting to further communication regarding their continued role in the proposed study, and answering all questions regarding study inclusion and exclusion criteria. All recruited subjects fulfilled the study criteria, requiring them to be at least 18 years of age, literate in the English language, and able to fully understand the experimental protocol and provide written consent. Additionally, each subject was required to fill out a standard Physical Activity Readiness Questionnaire (PARQ), indicating that they met the necessary standards of health for partaking in minimum to moderate levels of physical activity as required by the study.

Subjects deemed not eligible for the study due to failure to meet the required inclusion/exclusion criteria were discarded from the sample set and prevented from moving forward in the participant selection process. Conversely, those who successfully passed through the initial recruitment process by fulfilling the listed inclusion/exclusion criteria were added to the finalized list of participants on a first-come, first-served basis until the desired number of subjects was reached. Subjects included in the finalized participants list were then informed of the exact timing and location of their recording session. After arriving at the testing site, subjects were presented with a consent form, notifying the subject of the entirety of the logistics of experimentation. Given all parties involved were in agreement regarding the details of experimentation, the subject in question provided their signature on the consent form. Following the completion of each recording session, the enrolled subject was compensated in the amount of $35 for their participation before leaving the lab.

A convenience sample of 10 subjects was recruited for the current study. The participant pool consisted of 10 males aged 19 to 28 years old (mean age, 23.3 ± 2.67). Each subject was present at the lab for approximately 45 minutes, during which all testing and data collection for that specific subject was performed. During testing, subjects were evaluated based on cognitive and biomechanical performance to determine the effects of four distinct insole treatments on static and dynamic postural control. Static evaluations occurred within the adidas-ASU Center for Engagement Science Laboratory in the Mountain America Sun Devil Football Stadium. Subjects were subsequently taken outside the lab to complete the dynamic portion of testing outdoors, within the circular interior loop of the stadium, which functioned as a cyclical track during the second phase of experimental proceedings.

Risks during static data acquisition were negligible, whereas potential risks involved in the dynamic portion of the evaluation included sprains, strains, tears, and other standard physical activity-related injuries known to occur during regular exercise. Data collection devices included noninvasive wearable technologies for measuring auditory responses and various biomechanical measures. Rest breaks and water were given at regular intervals and any time upon the subject's request throughout the experiment. All methodologies and procedures employed throughout this study were carried out with the approval of the Arizona State University Institutional Review Board.

2.2 Experimental Design

2.2.1 Overview

The purpose of the current study was to assess the relative effects of four different insole conditions on cognition and locomotor adaptation during static and dynamic performance. Additionally, study investigators aimed to attain qualitative data on subjects' individual perceptions of the assigned insole treatments to potentially synthesize a correlation between perceptual emotion-based response and biomechanical performance.

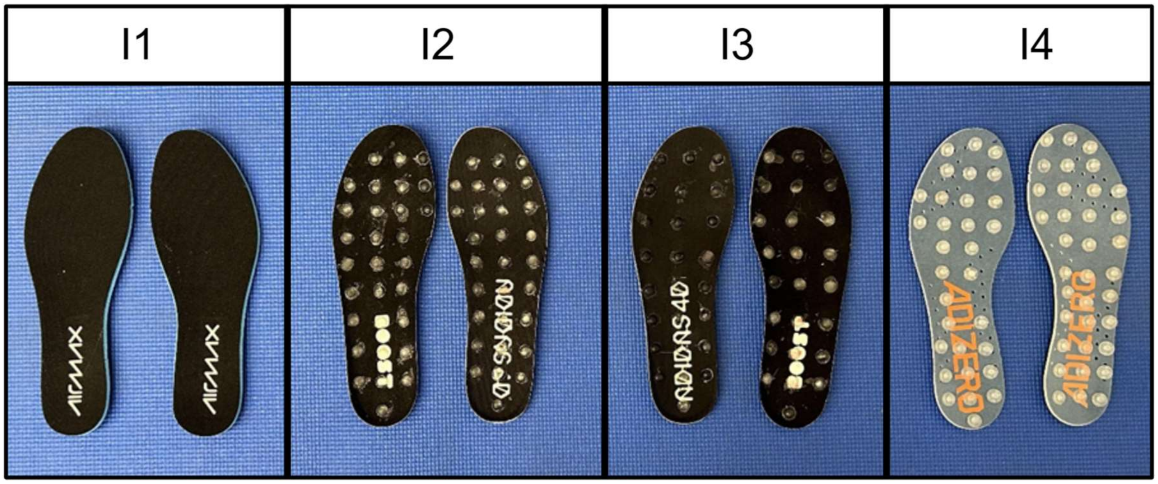

Figure 2. *The four insole treatments evaluated in this study consisted of the subject's own insoles to be used as a baseline experimental control (I1), in addition to three custom insoles with varying patterns of texture developed in-house to serve as experimental treatments (I2, I3, and I4). I1, I2, I3, and I4 are pictured left to right in the figure. An example pair of standard insoles is shown in the figure as a placeholder for the I1 treatment, which consisted of the subject's self-provided insoles.*

Subjects were first evaluated within the confines of the adidas-ASU Center for Engagement Science, where they completed a Visual Analog Scale Test (VAST). During the VAST, subjects were pseudorandomly presented with the four insole treatments tested in this study (Figure 2). Each subject was then instructed to rank their perceived level of surface roughness experienced while standing on each option. Following the VAST, testing continued within the confines of lab during which subjects were evaluated through a balance and stability test (BAST) which recorded postural sway along the mediolateral axis associated with each insole treatment in both the eyes open and eyes closed conditions. Subjects were then taken outside of the lab to the interior loop of the Mountain America Sun Devil Football Stadium, which was modified to function as a mock running track for the dynamic testing portion of experimentation.

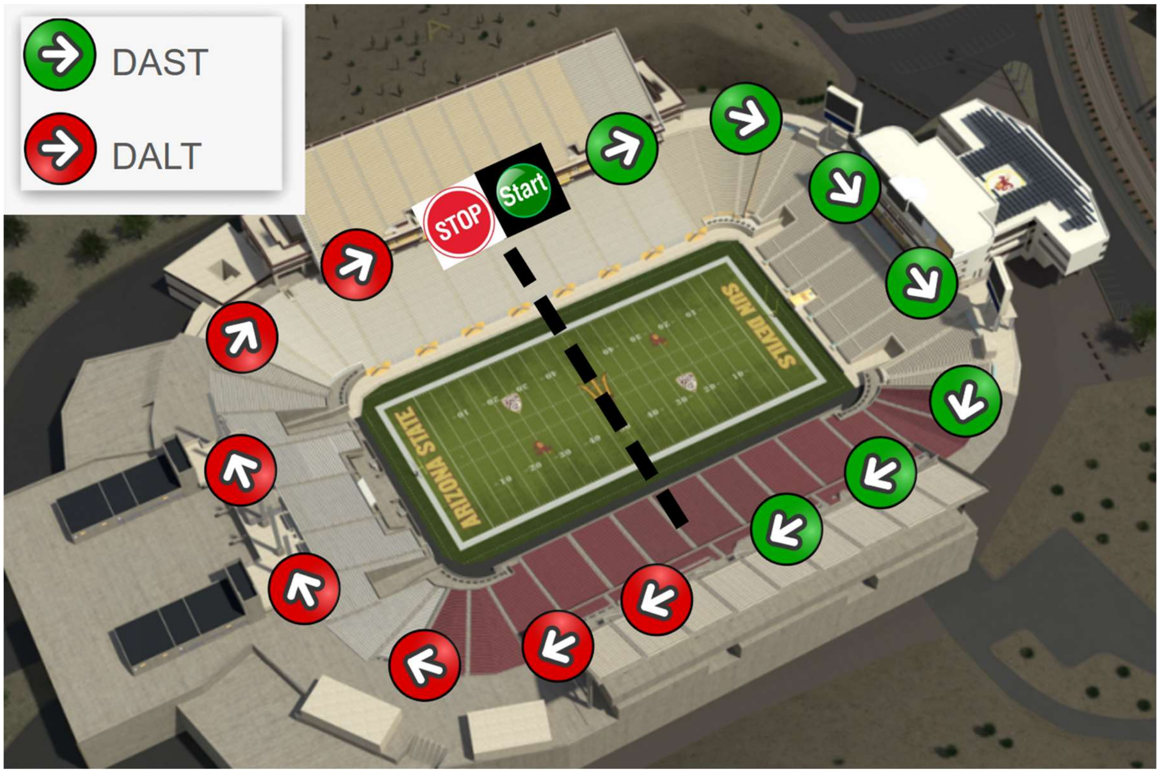

Figure 3. *Dynamic testing was done outdoors in Sun Devil Stadium's interior loop. This second phase of testing consisted of a Dual Task Assessment (DTA), which involved the continuous completion of a Dynamic Auditory Stroop Test (DAST) followed in succession by a Dynamic Adjusted Lane Test (DALT).*

The Dual Task Assessment (DTA), encompassing both the Dynamic Auditory Stroop Test (DAST) and the Dynamic Adjusted Lane Test (DALT) in succession required each subject to run a complete cycle around the interior loop of Mountain America Sun Devil Football Stadium (Figure 3). Subjects performed the DTA four times in their own preferred running shoes which were instrumented with one of the four insole treatments before the beginning of each cycle. Insole treatments were administered in a pseudorandomized order, and insole exchanges were completed during the 5-minute rest periods given to each subject in between DTA cycles. The DAST was administered during the first half-cycle of each DTA trial, followed by the DALT, which took place during the second half-cycle, requiring no stoppage in movement by the subject for each complete trial of the DTA.

It should be noted that although these experimental methods will expand on the DTA in its entirety, the full scope of this program of work included other assessments that will not be elaborated on further in this report. These adjacent testing efforts consisted of a multistage ankle proprioception test that took place within the confines of the adidas-ASU Center for Engagement Science subsequent to the VAST and BAST. Although this experimentation fell outside the scope of the current study, it is essential to acknowledge that the currently analyzed assessments were not completed in isolation. Eventually, results regarding variations in proprioceptive parameters under textured insole conditions may be presented in tandem with this report for a more holistic representation of the textured performance observed during the entirety of testing protocols. However, for now, the quantification of perception (VAST), static balance (BAST), and dynamic gait adaptability (DALT) provide a focused foundation for a standalone analysis into postural control and locomotor adaptation.

2.2.2 Visual Analog Scale Test (VAST)

Upon arriving at the lab, subjects were instructed to remove their shoes. Study investigators then removed the insole from the subject's self-supplied shoes to acquire the I1 insole treatment. The first test administered after insole treatment preparation was the VAST. During this test, the subject's insole (I1) and the three experimental textured insoles (I2, I3, and I4) were arranged in a pseudorandomized order. For purposes of the VAST, the insole treatments were not placed inside the subject's footwear and were laid on the floor as is.

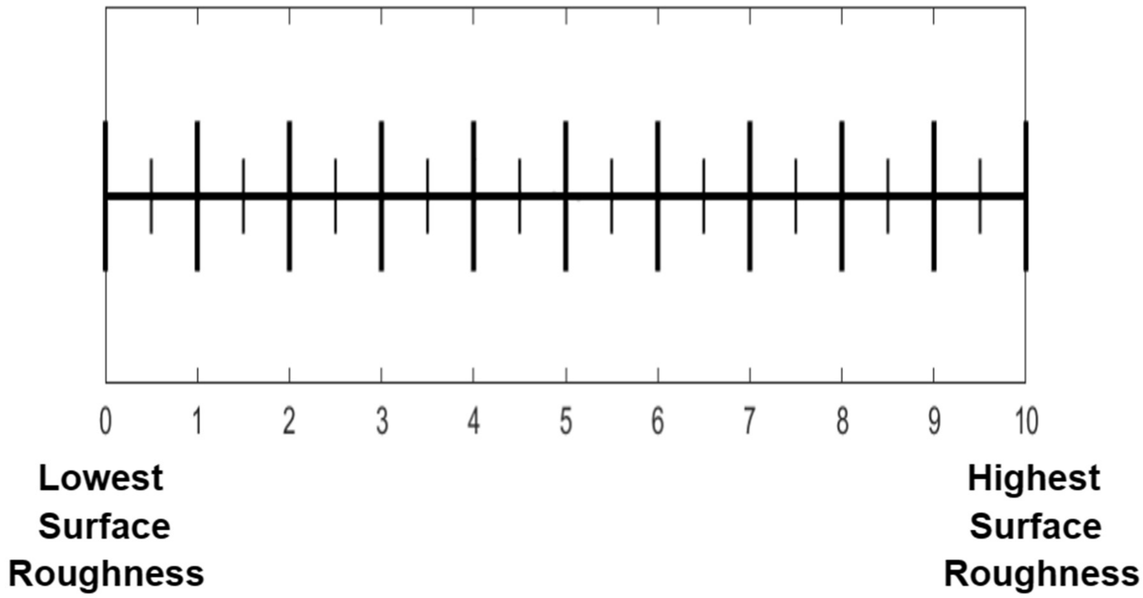

Figure 4. *The visual analog scale (VAS) was printed onto a single paper sheet and consisted of a 10 cm long number line with periodical dash markings at each whole number and a single (slightly shorter) dash marking spaced evenly between each whole number. The farthest left bound represented by the dash markings on the VAS was designated as value 0 and was labeled 'Lowest Surface Roughness.' The farthest right bound included was designated as value 10 and labeled 'Highest Surface Roughness.'*

A Visual Analog Scale (VAS) and a pencil were placed on a table in front of the insole treatments (Figure 4). Subjects were presented with the insole lineup and asked to freely evaluate each insole by using the pencil to make a corresponding mark on the visual analog scale indicating their perceived level of surface roughness experienced while standing on each of the treatments. The 0-value marking on the VAS indicated the lowest level of perceived surface roughness, whereas the 10-value marking indicated the highest.

There are many available methods for objectively quantifying the surface roughness of textured surfaces. Still, it has been shown that the deterministic roughness values reported by these numerical tests are not equivalent to a subject's perceived roughness value

(Bergmann Tiest & Kappers, 2007). Furthermore, numerical quantification methods for evaluating surface roughness would define the experimental textured insole treatments on a macroscale by analyzing nodule size, shape, and spacing variations. This would also be problematic as studies show that tactile perception is statistically dominated on the microscale, making variations in visually apparent surface features largely irrelevant and uncorrelated to the subjects' perceptual experience (Sahli et al., 2020). Therefore, any texture quantification methods outside of the subject's own haptic experience would not be useful for the purposes of this study as this figure would have no direct relation to a given subject's sensorimotor output during dynamic testing. Thus, the VAS was employed.

The wall facing the insole pairings was marked with four indicators, each aligned with a corresponding insole treatment. Subjects were instructed to affix their eyes onto the wall indicator corresponding to the insole pairing they were currently evaluating. Although subjects would undoubtedly have to view the insole briefly before standing on it, this experimental condition served as balance control by inducing a gaze stabilization effect (Morimoto et al., 2011; Pimenta et al., 2017). This allowed subjects to direct less of their cognitive capacity towards maintaining stability so that they could better concentrate on evaluating the surface roughness of each insole treatment. Additionally, stabilizing subjects' gaze during the VAST limited the amount of confounding visual stimuli that could arise if the subjects' eyes were allowed to wander freely. Eliminating as much multisensory interaction as possible would enhance overall attention on the direct perception of the insole treatments, allowing for a more constrained evaluation (Wesslein et al., 2014).

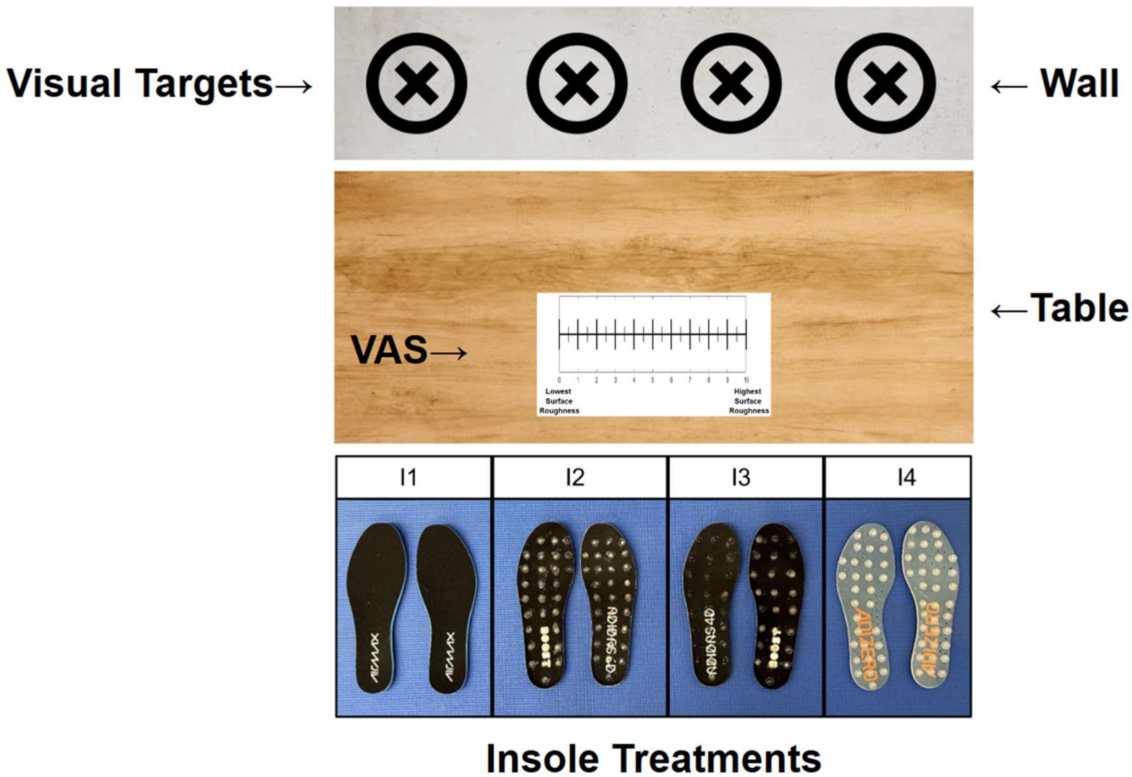

Figure 5. *Two-dimensional spatial distribution of all materials involved in the visual analog scale test (VAST), primarily consisting of the insole treatments being tested, the table containing the scale, and the wall-mounted visual stabilization markers*

Utilizing this experimental setup (Figure 5), the subject rated their perceived roughness for each of the four insole treatments, resulting in a total of four markings placed on the VAS. No parameters regarding standing durations or treatment times were implemented during the VAST. Although insole treatments were arranged in a pseudorandomized order before being presented, no starting insole treatment was indicated, and the subject was not instructed on any specific evaluation order. Instead, subjects were allowed to comfortably evaluate each treatment at their own pace, even going back and forth between the insole pairings and changing previously indicated VAS rankings as desired.

The VAST was concluded once the subjects were content with their perceptual ordering of the insole treatments. The VAS was then labeled with the subject's identification number and kept for post-processing analysis. To quantify these data, a measurement was taken from the left bound 0-value marking on the VAS to the marks indicated by the subject for each of the four insole treatments. The treatments would then receive a score between 0 and 10 corresponding to the subject's self-reported VAS markings, indicative of their perceived surface roughness while standing on each pair of insoles.

2.2.3 Balance and Stability Test (BAST)

Following the VAST, subjects remained in the confines of the adidas-ASU Center for Engagement Science to carry out the BAST, which evaluated subjects' static postural control while instrumented with each insole treatment during eyes open and eyes closed bilateral standing balance. Dissimilar from the VAST, the subjects' footwear was instrumented with each of the administered insole pairs, and the full apparatus was worn for each trial of the BAST. Subjects completed four total trials of the BAST, which involved data sampling during the eyes open and eyes closed bilateral standing balance conditions for each of the four insole treatments, which were once again administered in a pseudorandomized order.

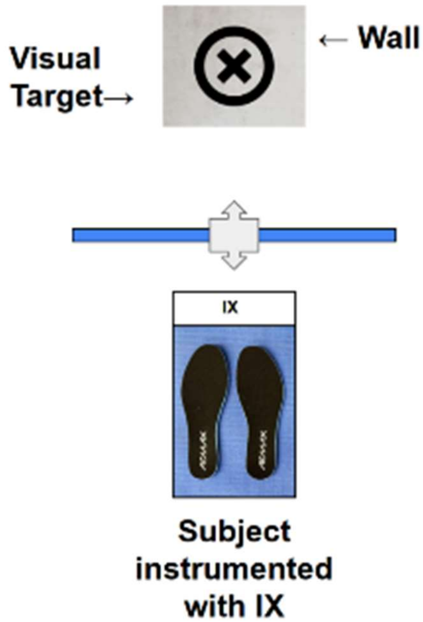

Figure 6. *Two-dimensional spatial distribution of the experimental design employed during the balance and stability test (BAST) involving visual representation of the subject with the currently tested insole treatment, the divider separating sampling and non-sampling testing epochs, and the corresponding gaze stabilization target.*

Once instrumented with the first insole treatment assigned during the BAST, subjects positioned themselves with their toes facing a blue line divider marked off on the lab floor and fixed their vision toward the corresponding wall-mounted gaze stabilization marker (Figure 6). The gaze stabilization markers employed in the BAST were identical to those utilized during the VAST. They provided the same function of eliminating confounding visual stimuli that could arise during testing. Subjects were instructed to visually align themselves with the gaze stabilization targets for all BAST testing protocols. Once in position, subjects would be audibly cued by four computer-generated beeps that indicated movement back and forth across the blue line divider.

Upon hearing the first computer-generated beep, subjects stepped over the blue line divider and crossed their arms across their chest while maintaining eye contact with the wall-mounted markers. This marked the first 10-second sampling epoch, during which subjects' acceleration was quantified by a mobile phone running the Physics Toolbox Sensor Suite accelerometer application package (*Vieyra Software*, n.d.). The phone running the inertial sensing operations was placed in a secured pouch affixed to the subject's waist prior to each trial. After this first 10 seconds of eyes open standing bilateral balance, a second computer-generated beep was heard, instructing subjects to step back to their starting position behind the blue line divider for a 10-second rest period.

After these 10 seconds of rest, a third computer-generated beep was heard, instructing subjects to once again step over the blue line divider for the second sampling epoch, which entailed identical procedural demands to the first sampling epoch, with the added constraint that the subject would now be required to complete this 10-second bilateral standing balance epoch with their eyes closed. Following these 10 seconds of eyes-closed bilateral standing balance, a fourth and final computer-generated beep was heard, indicating the culmination of a single BAST trial. This procedure was replicated four times to capture data identically for all four insole treatments, with insole exchanges being carried out between each trial.

2.2.4 Dynamic Auditory Stroop Test (DAST)

After completing the BAST, subjects were taken outside the lab and into the Mountain America Sun Devil Stadium interior loop to begin the dynamic testing portion of experimentation. Dynamic testing consisted of four DTA trials, in which each subject's performance was evaluated under each of the four insole treatments. Before starting the DTA, subjects' shoes would be equipped with one of the four insoles, pseudorandomly assigned prior to testing. During the initial preparatory period, subjects would also be instructed to download the audio file responsible for administering auditory cues to the subject via a corded headset during the DAST/first half of the DTA (Baldwin et al., 2022). The DAST audio file was downloaded onto the subject's personal mobile phone, and the corded headset was typically self-supplied; however, a pair was provided by the investigators if necessary. This concluded the initial setup of the individual's wearable testing apparatus for the entirety of the DTA.

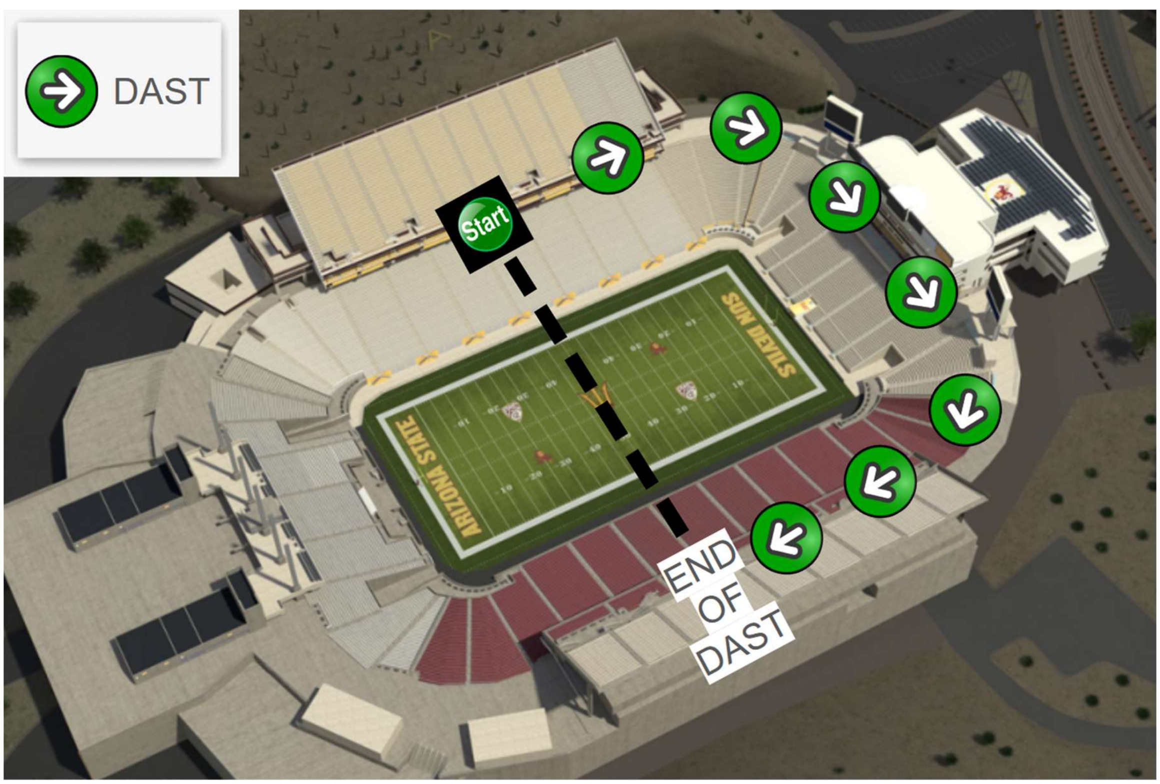

Figure 7. *The first half-cycle of the dynamic testing assessment (DTA) consisted of the dynamic auditory Stroop test (DAST), which required the subject to complete a self-paced run from the starting line to the contralateral 50-yard line mark on the other side of the stadium while undergoing an auditory-based psychophysical assessment.*

Once instrumented with all wearables necessary for the completion of the DTA, subjects then lined up at a starting mark in line with the 50-yard line of the stadium field, where they began the DAST by initiating a clockwise run around the interior stadium loop (Figure 7). Subjects were instructed to complete the DTA at a comfortable pace, which they believed they could maintain consistently for the duration of dynamic testing. At this point, investigators signaled the subject to initiate their run and begin the DTA, starting with the DAST subtask. Upon receiving this signal, subjects simultaneously pressed the start button on their mobile phone, triggering the commencement of the DAST audio file, and began running. Subjects held their mobile phones in their right hand for the entirety of the DTA, while the DAST audio file administered the DAST via headset for the first half cycle of each DTA trial, or approximately until the subject reached the contralateral 50-yard line directly opposite their starting position on the interior loop.

The DAST evaluated each subject's cognitive acuity by quantifying their ability to react to randomly administered auditory stimuli. The DAST audio file was developed in-house and served as a means for reducing the confounding effects that occur when employing the commonly used Visual Stroop Test (VST) during dynamic evaluations. Since the subject is already visually occupied by the task of dynamic regulation as a result of natural locomotion, implementing a VST would effectively introduce an additional visual perturbation. The subject would subsequently be forced to adapt to visual stimuli arising from their dynamic environment in addition to the visual stimuli introduced by the VST, thus creating a significant degree of structural interference during the test (Bock & Beurskens, 2011; H.-C. Chen et al., 1996; Worden et al., 2016). Conversely, the DAST serves as a solely auditory perturbation preventing the recruitment of identical perceptual structures for successful signal differentiation (Kahneman & Chajczyk, 1983; Worden et al., 2016), allowing for a more defined analysis of the subject's performative measures in both the cognitive and biomechanical domains.

Two separate cues, the word 'Right' and the word 'Left,' were administered through the subject's headset 8 times each, for a total of 16 administered cues throughout the entirety of each DAST. The cues for the DAST audio file were recorded using a dual-channel stereo recorder, allowing each cue to be administered to an individual side of the subject's headset instead of being heard simultaneously through both. Half of the total 16 administered auditory cues were congruent in meaning and location. In this instance, the 'Right' cue was heard in the right ear, or conversely, the 'Left' cue was heard in the left ear. For the other 8 cues administered during the DAST, the meaning-location relationship of the stimulus was incongruent. The scenarios captured in this case were the 'Right' cue heard in the left ear or, conversely, the 'Left' cue heard in the right ear. The sequence of the congruent and incongruent meaning-location signal pairings was completely randomized. The timing between the administered stimuli was also randomized within a range of 2.5 seconds to 5 seconds.

Immediately upon hearing each of the 16 total auditory cues, subjects were instructed to audibly respond with either 'Correct' for congruent meaning-location pairings or 'Wrong' for incongruent meaning-location pairings. The application administering the DAST audio file recorded these responses through a built-in remote phone recording device, which digitized both the administered auditory stimulus and subject response into a single sound envelope. The envelope processed the data for response accuracy and response reaction, defined as the time period between the peak of the administered auditory stimulus and the detection of the subject response. Once all 16 auditory cues contained in the DAST audio file were administered and responded to, the DAST was concluded. This occurred approximately as subjects reached the contralateral 50-yard line marking, directly opposite their starting position, where they would then begin the DALT. The subject's headset and personal mobile phones served no function following this checkpoint.

2.2.5 Dynamic Adjusted Lane Test (DALT)

After reaching the contralateral 50-yard line marking on the opposite side of the interior stadium loop, subjects would have completed the DAST and the first half cycle of the DTA. Following this, the DALT, constituting the second half cycle of the DTA, would commence in immediate succession. The DALT required the modification of the second half cycle of the stadium's interior loop to include three separate gait perturbations for the subject to adapt to during the ladder half of the DTA. Each of the three gait perturbations consisted of a confined running lane measuring 10 meters long and 0.5 meters wide marked off at equidistant locations (approximately 50 meters apart) on the track by evenly spaced orange indicators.

Natural gait is typically automated and habitual for healthy individuals. Conversely, the experimental apparatus employed in the DALT functions to alter standard locomotion by inducing a complex gait akin to the paradigm seen in dynamic tasks involving object avoidance. Previous studies reflect the larger cognitive load that an individual experiences during complex gait by reporting the many minute motor adjustments that occur when approaching a perturbation (Corporaal et al., 2016). These adjustments are directly result from the body's ability to incorporate proprioceptive feedback via communication with the CNS (Bertrand-Charette et al., 2022; Hinton et al., 2020; Hubbuch et al., 2015).

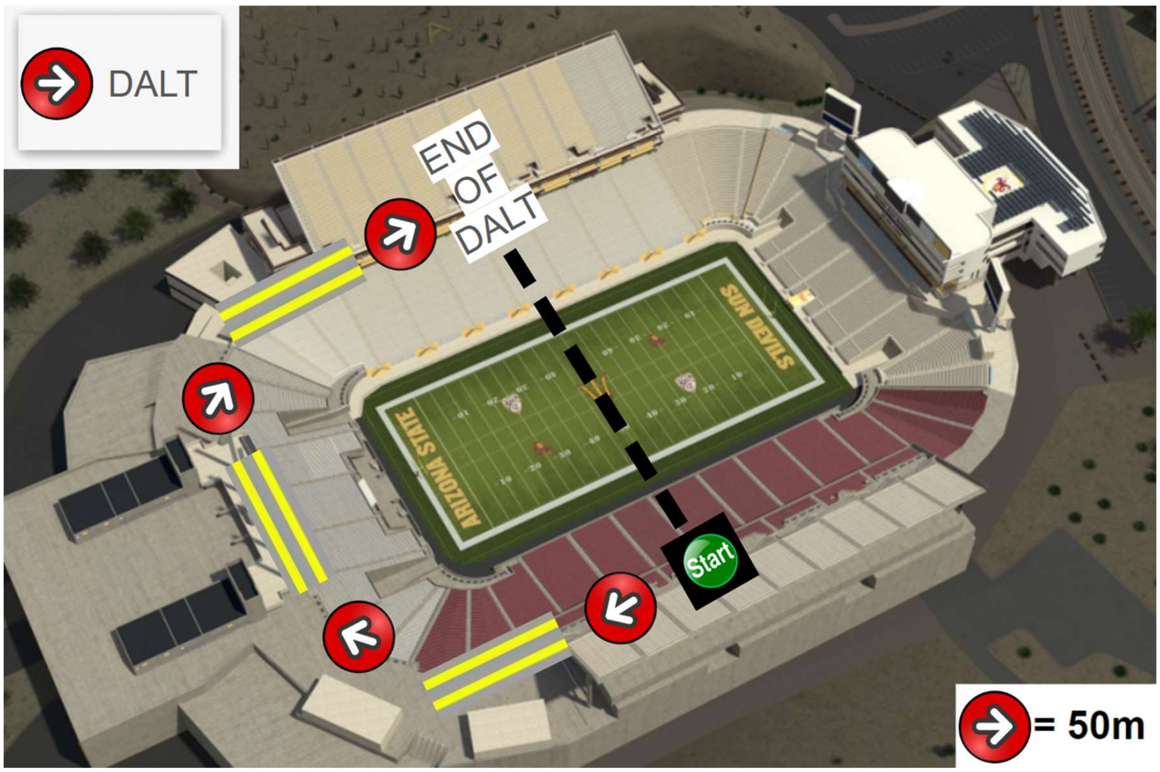

Figure 8. *The second half-cycle of the dynamic testing assessment (DTA) consisted of the dynamic auditory lane test (DAST), which required the subject to complete a self-paced run from the contralateral 50-yard line mark on the other side of the stadium back to the starting point while undergoing an induced complex gait assessment.*

The narrowed lane segments were placed at three symmetrical locations around the horseshoe-shaped track employed in the DALT (Figure 8). The subject would encounter the first narrowed lane segment approximately 50 meters after beginning the DALT. Following the completion of this initial 50-meter free run and exiting the first 10-meter lane perturbation, the subject would repeat this order of events another two times before concluding the test with a final 50-meter free run. By following a sequence of free run - narrowed lane - free run, the DAST creates a consistent half-loop running test structured as follows: 50-meter free run, 10-meter lane, 50-meter free run, 10-meter lane, 50-meter free run, 10-meter lane, 50-meter free run. The execution of this procedural structure marked the finish point of the DAST and, consequently, the DTA, as subjects completed one full cycle around the stadium's interior loop, thus returning to the initial DTA starting point. At this point, the subject would be given a 5-minute rest period while investigators instrumented their shoes with the next insole treatment for the subsequent DTA. As previously outlined, the subject completed four full cycles around the interior loop of the stadium, translating into four trials of the DTA and, consequently, four trials of both the DAST and the DALT, ensuring that all procedural measures were carried out under all four administered insole treatments.

Figure 9. *During the dynamic adjusted lane test (DALT), a 10-meter-long and 0.5-meter-wide confined lane intervention was introduced three times at equidistant locations around the interior loop of Mountain America Sun Devil Football Stadium. Subjects traversed the DALT lane interventions during the second half of the assigned dual-task assessment (DTA).*

It should be noted that the 10-meter lane distance employed in the DALT procedure was an intentional constraint (Figure 9). This distance has previously been used for analyzing the nuances and subtle changes in gait parameters during commonly administered timed-up motor function tests (Hoskens et al., 2019; Krosschell et al., 2022; Pereira et al., 2016). To determine how subjects adapt their gait to the perturbations introduced during the DALT, a similar analysis is needed, making the 10-meter distance a valid figure for the purposes of experimentation. 10-meter run tests are also commonly used in studies seeking to attain baseline performative measurements in athletic populations (Ilhan et al., 2023; Suits et al., 2024; Williams et al., 2023). Moreover, run performance at the 10-meter distance has also been associated with several other kinetic and kinematic parameters, such as peak jumping velocity and rate of force development within athletic populations (Marques & Izquierdo, 2014). The broad backing for this measurement across multiple sports-based evaluations and its potential link to other performative metrics make it an optimal figure for widening the scope of application for the current study.

By introducing a narrowed space for subjects to adhere to during their run, the DALT effectively forces subjects to slow down and adjust to the upcoming perturbations. The lanes on a standard 400-meter running track are typically 1.22 meters in width, allowing the athlete to run freely during competition without feeling constrained by the left and right bounds of the lane. Decreasing this standard width by a factor of almost half (0.41) for an induced lane width of 0.5 meters significantly hampered the subject's ability to run freely within the confined lanes introduced during the DALT. The goal of constraining the subject to this set of confined lanes was to measure their relative ability to adapt to induced perturbations under each of the four insole conditions.

A GoPro camera set to record at 1080 pixel resolution continuously was positioned at each of the three lanes in a configuration that allowed for a field of view capable of capturing the entirety of the 10-meter lane in addition to the 10-meter distance leading up to the lane. The GoPro footage captured at each of these 20-meter extended segments was used to quantify how efficiently a given subject adapted their movements to pass through the narrow confines of the lane interventions. To perform this calculation, each individual's velocity during the 10 meters leading up to the narrowed lane, velocity1 (V1), and their velocity during the 10-meter narrowed lane, velocity2 (V2), was measured using Adobe Premiere Rush video analysis software. The percent difference between these two velocities was then recorded to synthesize a final value representative of the subject's percent change in velocity between the 10 meters leading up to the gait and the 10 meters within the confines of the gate (%ΔV).

The %ΔV metric served as a mock variable for the subject's estimated deceleration when approaching and traversing each perturbation. For example, a larger recorded %ΔV meant that the subject slowed down considerably when encountering the narrowed lane and, therefore, was not as quick to adapt their gait to the upcoming perturbation. Conversely, a smaller recorded %ΔV indicated that the velocity recorded when the subject approached the lane intervention was not dissimilar from their velocity captured during the lane intervention. In this case, it can be reasonably assumed that subjects efficiently adapted their gate in the 10 meters leading up to the perturbation, allowing them to maintain a more consistent speed while running through the narrowed lane without the need for excessive deceleration. Another way to think of this parameter is as an estimated quantification of subject reaction time as needed to adapt from natural to complex gait due to the experienced perturbations.

By leveraging the high level of gait adaptability in healthy individuals, the DALT presents a viable option for uncovering the neural mechanisms regularly employed to adjust lower limb kinematics in the presence of naturally occurring obstacles or perturbations. Furthermore, variations in gait parameter alterations under the different insole treatments will provide a basis for linking the underlying mechanisms of locomotor adaptation to individual sensory perception, paving the way for further research into the potential performative benefits of this correlation. Evidence supporting such a relationship could be readily incorporated for applications during athletic performance as trained athletes face a constant requirement for gait adaptation to facilitate quick movements within an optimal reaction time threshold. If performative metrics synthesized in this domain were readily correlated to scales of perception, novel products could be more readily developed to enhance both variables in tandem by adhering to their dependent relationship.

CHAPTER 3

RESULTS

3.1 Scope of Analysis

It should be noted that the results of this program of work will strictly apply to the VAST, BAST, and DALT. All data gathered during the DAST will be securely stored within the ASU Center for Engagement Science and reviewed separately. The DAST analysis will eventually be presented in tandem with the results of the DALT to provide a more final and holistic account of the tasks involved in the DTA. While both the DAST and DALT subtasks offer insight into the cognitive processes underlying dynamic reaction, this analysis will focus on the efficiency of motor adjustments carried out in response to visual perturbations, as seen in the DALT. The analysis of cognitive response due to auditory perturbations induced in the DAST will be completed at a later date and used to supplement the DALT results in order to synthesize a full report on the effects of textured insoles on dynamic audiovisual response and reaction time. However, for now, only a concise recounting of the statistical analyses carried out in the VAST, BAST, and DALT will be necessary for the purposes of this report on postural control and locomotor adaptation.

3.2 Visual Analog Scale Test (VAST) Analysis

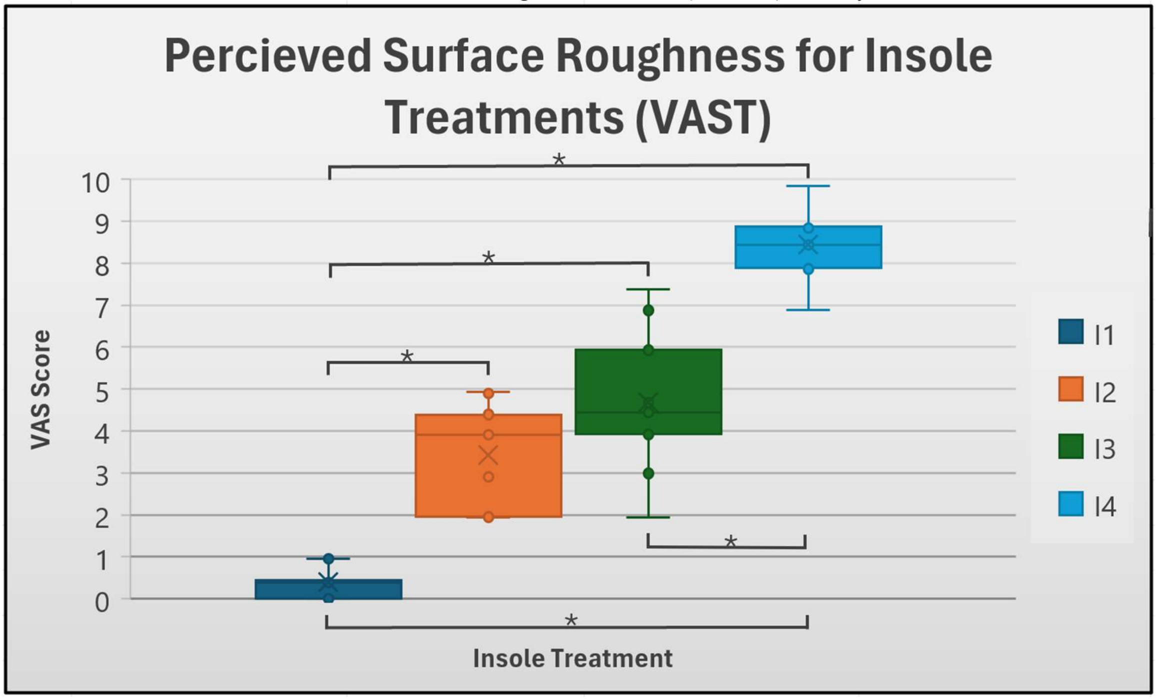

Figure 10. *Box chart depicting subjects' self-reported perceived surface roughness for each insole treatment evaluated during visual analog scale test (VAST) protocols. Insole treatment group specifications, including mean markers, mean lines, inner points, and outliers, are also shown.*

The VAST saw subjects rate each insole treatment on a visual analog scale of perceived surface roughness. The scale ranged from 0 (least rough) to 10 (most rough). Measurements were taken from the 0 marking to the points marked on the scale by the subject for each insole pairing. This linear measurement was recorded as the subject-reported VAS score. By pooling the data from all participants, mean VAS scores were calculated for each insole condition and reported in a box and whisker chart (Figure 10).

Mean VAS scores for each insole category are as follows: I1 = 0.39±0.37; I2 = 3.42±1.26; I3 = 4.68±1.78, I4 = 8.44±0.83. A set of paired t-tests showed all insole pairings demonstrated a difference in surface roughness that was statistically significant when compared to all other conditions, with the exception of the I2, I3 comparison ($p = 0.09$) which reported no significant difference in subject-reported perceived surface roughness. However, given the linear trend of increasing perceived surface roughness throughout the insole order I1 to I4, it can be reasonably assumed that the I2, I3 comparison will most likely reach significance once a complete study sample of 20 subjects is evaluated. All reported p-values statistically established significant differences between insoles are as follows: I1 vs. I2 ($p = 0.11E-3$); I1 vs. I3 ($p = 2.25E-05$); I1 vs. I4 ($p = 8.35E-10$); I2 vs. I4 ($p = 1.03E-05$); I3 vs. I4 ($p = 0.26E-3$).

Interpreting the apparent linear increase in perceived surface roughness observed during the VAST reveals that the average reported surface roughness increased by a factor of almost three (2.68) throughout the insole ordering I1 to I4. Overall, insole treatments were highly related to specific VAS scores, with I1 being associated with lower VAS scores (accordingly so, given this was the baseline control treatment with no texture), I2 and I3 being associated with intermediate values of perceived roughness (no significant difference in I2, I3 comparison), and the I4 treatment reporting a significantly higher mean VAS score when compared to all other treatments. However, this correlation is not necessarily significant, given that the insole treatments were labeled I1 through I4 arbitrarily. Coincidently, this treatment order was linearly correlated to the average perceived roughness reported by the sample population. Still, this result does not indicate anything meaningful regarding apparent performative differences in the data, but it does suggest that the sensory feedback acquired from subjects' external perception is, in a way, modulated by the addition of texture. Correlating this conclusion with subjects' physical performance on the BAST and DALT will reveal more information about the nuances of integrating this observed sensory augmentation effect.

3.3 Balance and Stability Test (BAST) Analysis

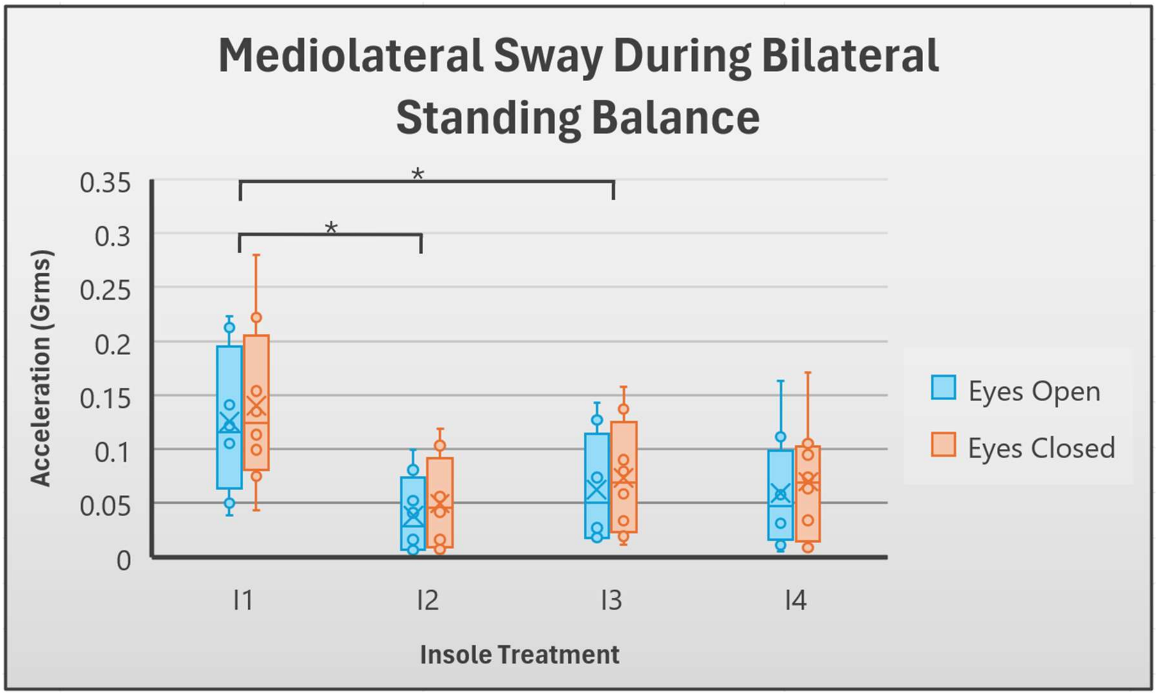

Figure 11. *Box chart depicting root mean squared acceleration (GRMS) averaged across the mediolateral axis during eyes open and eyes closed conditions for all four insole treatments.*

The BAST was the first test, following the VAST, that sought to determine whether individual perception could be correlated to motor response during a physical assessment. In this case, the BAST measured mediolateral postural sway during 10-second epochs of eyes open and eyes closed standing balance for each subject under all four insole conditions (Figure 11). Root mean squared acceleration (GRMS) was used to quantify mediolateral sway for each subject during the BAST. GRMS was then averaged across the entire sample for each insole treatment and testing condition (eyes-open, eyes-closed) to acquire a holistic report of stability throughout the population.

Mean GRMS scores sampled in m/s^2 for each insole category during the eyes open condition are as follows: I1 = 0.13±0.07 m/s^2, I2 = 0.04±0.04 m/s^2, I3 = 0.06±0.05 m/s^2, I4 = 0.06±0.05 m/s. Similarly, mean GRMS scores sampled in m/s^2 for each insole category during the eyes closed condition are as follows: I1 = 0.14±0.08 m/s, I2 = 0.05±004. m/s^2, I3 = 0.07±0.05 m/s^2, I4 = 0.07±0.05 m/s^2. These results showed that the mean mediolateral postural sway for all insole treatments was increased during the eyes-closed condition in the absence of any gaze stabilization markers. This conclusion is supported by the current literature and adds to the validity and replicability of the BAST (Morimoto et al., 2011; Pimenta et al., 2017).

After a series of paired t-test evaluations, the results revealed that the I2 ($p = 0.01$) and I3 ($p = 0.30$) insole treatments led to a statistically significant reduction in mediolateral postural sway compared to the I1 baseline control in both the eyes open and eyes closed BAST conditions. No other insole treatment comparisons under either the eyes open or closed conditions reached significance during the BAST. An interesting observation from these data points was that the I3 and I4 treatments reported similar figures for GRMS mean and standard deviation. However, only the I3 treatment showed a significant difference compared to the I1 baseline control. Further analysis revealed that I4 did not reach significance due to the presence of significant outliers and standard error within the raw data.

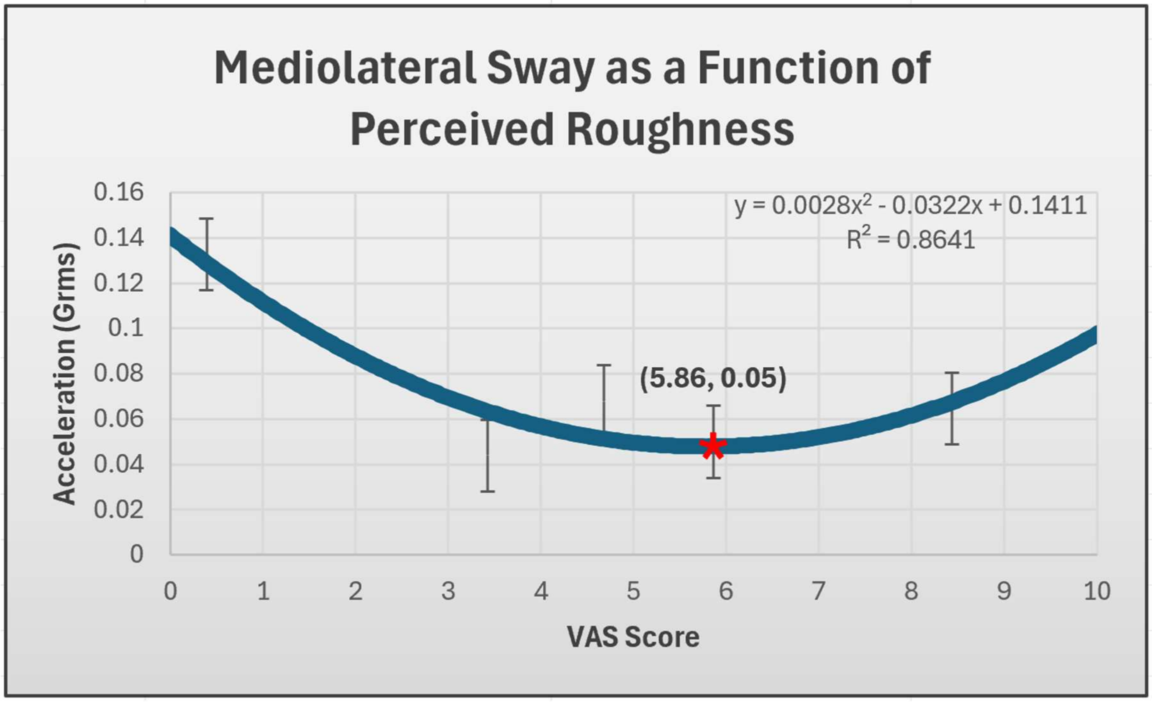

Figure 12. *Polynomial mixed-effect regression correlating the visual analog scale test (VAST) results with the mediolateral sway variations observed during the balance and stability test (BAST). The observed continuum establishes interplay between each insole treatment's perceived surface roughness and corresponding static postural control.*

To produce a cumulative representation of the correlative results between postural control and perceived roughness observed during the BAST, GRMS values from both the eyes open and closed condition were averaged for simplicity. Upon this refinement of the dataset, mediolateral sway reduction observed during the BAST was reported as a function of perceived surface roughness measured during the VAST (Figure 12). A polynomial mixed effect regression was used to model the continuum that resulted from this extrapolation of results seen during the BAST and VAST. The correlative continuum followed function, $y = 0.0028x^2 + 0.0328x + 0.1416$, which when minimized indicated that a perceived surface roughness measured through a VAS score of 5.86, would incorporate the ideal texture design for optimizing static postural stability at least within the experimental confines of the BAST protocols and evaluation methods.

3.4 Dynamic Adjusted Lane Test (DALT) Analysis

Results for the DALT, employed during the second half-cycle of the DTA, were representative of the sample set's average ability to adapt their gait when introduced to the three confined lane spaces traversed during a standard lane running assessment. When quantifying results for the DALT, the %ΔV was calculated to estimate how well each subject adapted to the introduced lane perturbations while wearing each of the four insole treatments. V1 represented the velocity measured during the 10-meter distance leading up to the narrowed lane space, and V2 represented velocity within the confined 10-meter lane itself. The rationale behind this arithmetic was that as subjects approached the narrowed lane, their natural pace, V1, would be engaged and observed during the 10-meter segment leading up to the lane. Then, the subjects' V2 pace would be recorded during the 10-meter lane. This figure was associated with the complex gait employed in order to adjust natural locomotion so as to adhere to the confined space.

V2 was an inherently lower average recorded pace for the sample population, given that this was the running segment in which natural gait was perturbed. By quantifying %ΔV, a difference is reported that shows to what degree subjects decreased their velocity when approaching the narrowed lane. Therefore, a larger %ΔV value, indicated that subjects slowed down significantly when approaching the narrowed lane, demonstrating a reduced ability to adapt their gait to the oncoming perturbation. Conversely, a minor %ΔV, indicated that subjects efficiently adapted their gait to the oncoming perturbation, requiring them to slow down to a lesser degree when approaching the confined lanes. This result showed an increased level of readiness during the switch from the natural gait employed throughout the 10-meter approaching distance to the complex gait required within the 10-meter lane.

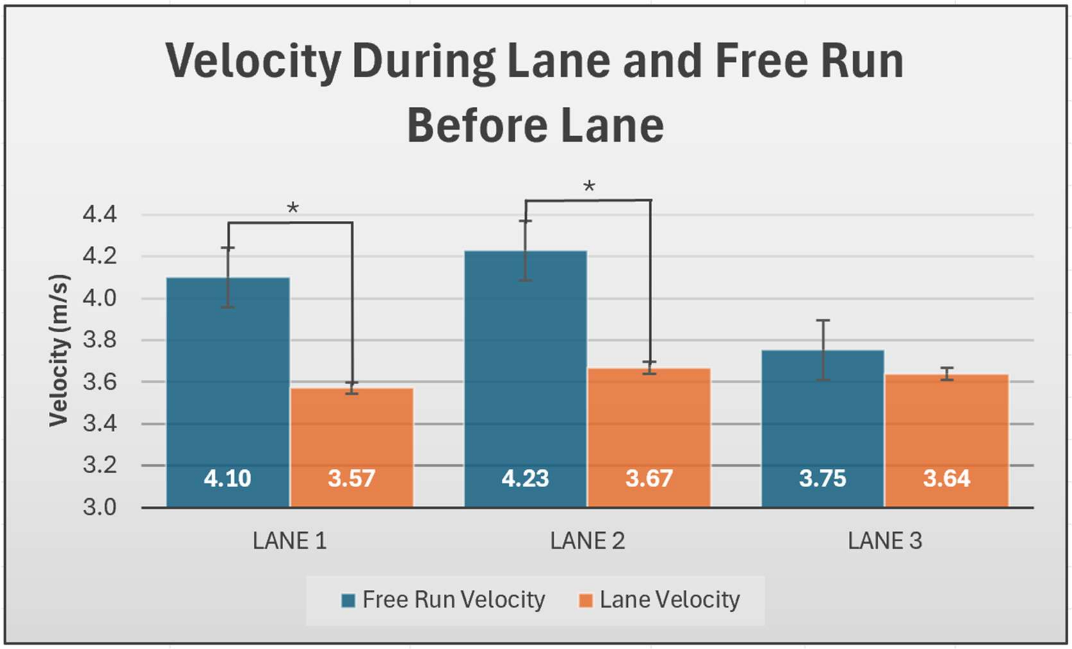

Figure 13. *Average velocities for 10 meters leading up to each administered lane perturbation compared to average velocities reported during 10-meter confined lane perturbation during the dynamic adjusted lane test (DALT).*

Before analyzing data across all three lanes, lane-specific data was computed to demonstrate the free run and confined lane velocities resulting from each narrowed lane intervention (Figure 13). When viewing these data, it can be seen that average velocities for both the free run and confined space categories of the acquired data from lane three are considerably lower than the corresponding numerical figures resulting from an identical analysis of the lane one and lane two results. Furthermore, during the DALT, it was assumed that velocity would significantly decrease as subjects approached the narrowed lane perturbations, given that they would have to adjust their motor movements to adhere to the half-meter running lane by transferring to a complex gait pattern. However, when comparing the total sample set of data points for all segments (free run and confined lane space) of all the lane perturbations (lane 1, lane 2, and lane 3), it was revealed that lane 1 ($p = 9.65E-06$) and lane 2 ($p = 2.03E-06$) demonstrated statistically significant differences in velocity during their respective free run and confined running sections, but lane 3 showed no significance ($p = 0.34$). This indicates that subjects experienced no significant decrease in velocity when adapting their gait pattern to adhere to the final lane perturbation introduced during the DALT. The paired t-tests administered to conclude this information indicated that the free run and confined lane segment velocity observed during lane 3 varied substantially and were hardly even comparable to the corresponding results seen from lane 1 and lane 2 in this regard.

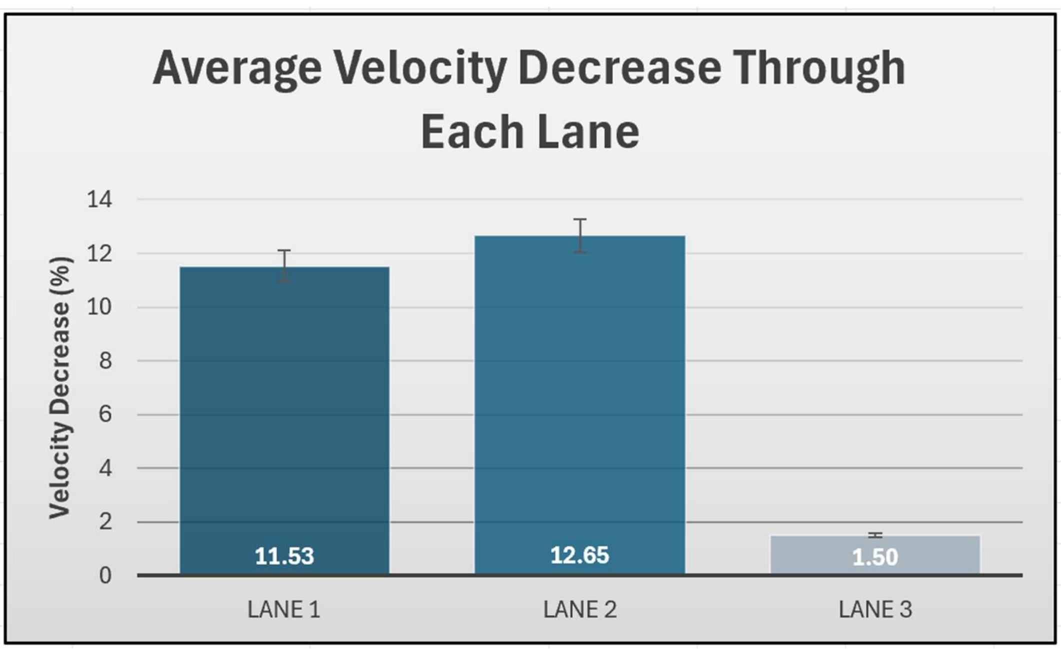

Figure 14. *Average reported percent velocity decreases during each of the three confined lane spaces introduced during the dynamic adjusted lane test (DALT).*

It was initially hypothesized that the lack of significant difference in the free run and confined lane segment velocities seen in Figure 13 resulted from a learning effect that climaxed on the final lane perturbation introduced during the DALT. However, upon holding the data up to further scrutiny, it was clear that lane 3 was a source of invalid and confounding data. In alignment with this conclusion, quantifying lane-specific percent velocity decreases showed that lane three, on average, induced a percent velocity decrease up to 10% lower than that observed during lane 1 and lane 2 (Figure 14.). Furthermore, the proposition of a learning effect was debunked through the observation that lane 1 and lane 2 saw no pattern of improved adaptability, thus identifying the data acquired from lane 3 as a clear outlier throughout the DALT analysis. With these evidence-based conclusions, the investigators omitted all lane 3 data points for further consideration in terms of the adaptability assessment carried out in the DALT.

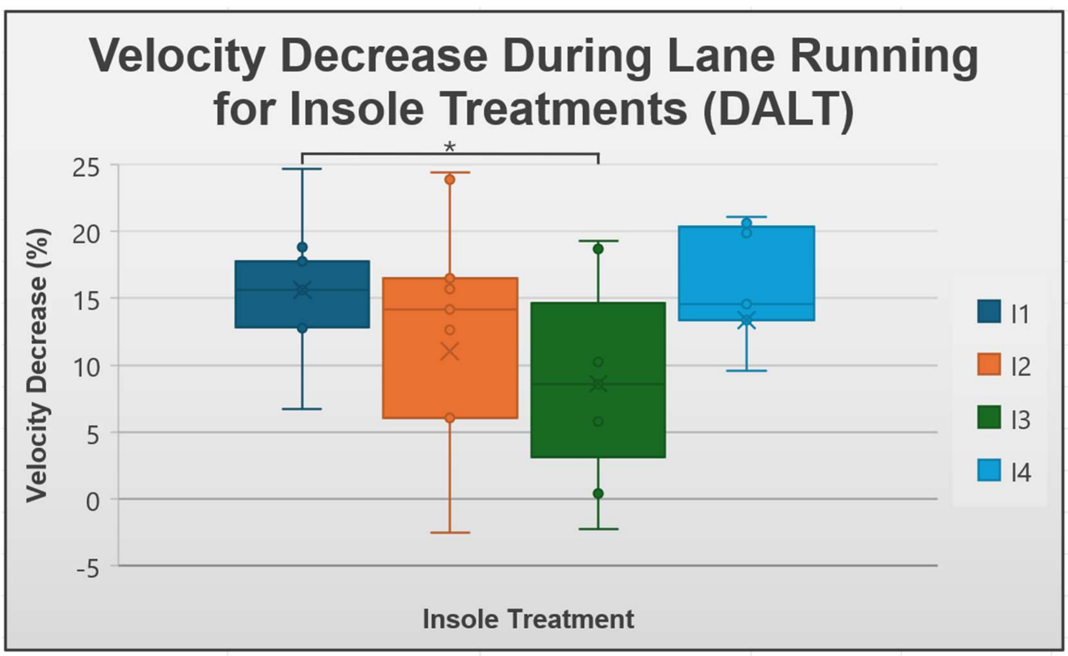

Figure 15. *Percent velocity* decrease (%ΔV) between *the 10-meter free run (V1) and the 10-meter confined lane space (V2) recorded in meters/second for each insole treatment during dynamic adjusted lane test (DALT). Smaller %ΔV values indicate an elevated ability to adapt gait and vice versa.*

DALT results were computed by evaluating each subject's performance during only the first and second introduced lane perturbations. This was done for all four insole treatments to produce a comprehensive %ΔV for each subject under each insole condition. %ΔV metrics were then averaged across the entire sample to derive a holistic average percent velocity change under each insole condition for the entirety of the subject pool. These results were reported in a box and whisker plot to visually correlate each insole treatment to their corresponding value of %ΔV (Figure 15). Mean %ΔV scores for each insole category are as follows: I1 = 15.60±4.90 %, I2 = 11.03±11.86 %, I3 = 8.60±7.23 %, I4 = 13.36±10.55 %.

A paired t-test showed that the I3 treatment induced a statistically significant ($p = 0.02$) minimization of the percent velocity reduction employed when switching from natural to complex gait during the DALT perturbation adaptation phase. In essence, this significance demonstrates the textured intervention provided by the I3 treatment enhanced the adaptability of the subjects' gait. No other statistically significant results were established that differentiated the %ΔV for a single insole treatment from the other tested pairs. This was concluded as a result of a set of paired t-tests that produced the following significance values: I1 vs. I2 ($p = 0.16$); I1 vs. I4 ($p = 0.33$); I2 vs. I3 ($p = 0.26$); I2 vs. I4 ($p = 0.36$); I3 vs. 4 ($p = 0.17$). Although the sample population of 10 recruited for this study was sufficient to establish a performative difference in the I1, I3 comparison, a few patterns also emerged that appear to be promising and will hopefully yield more definitive information once more subjects are tested.

Specifically, the I2 and I3 treatments both seemed to induce improvements in reported %ΔV measures; however, only I3 reached significance in its comparison to the I1 baseline control. With that being said, the I1, I2 comparison did have the second lowest p-value behind the I1, I3 comparison, indicating that I2 could potentially induce a statistically significant reduction in %ΔV once more data is acquired from a complete sample size. Nevertheless, these data showing visually apparent enhancements in adaptability through the I2 and I3 treatments is a significant preliminary finding that advocates for the existence of a textured-enhanced performance in this sample; however, more compelling information can be found by relating the %ΔV measures directly to perceived surface roughness instead of to the arbitrarily assigned insole conditions.

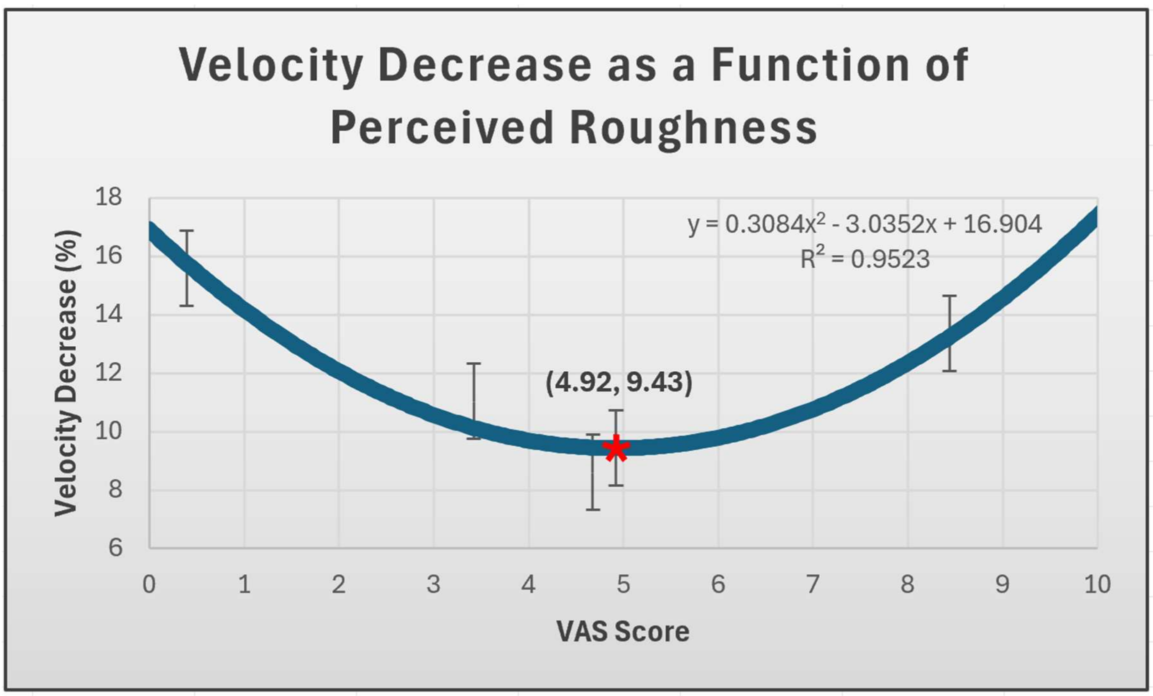

Figure 16. *Polynomial mixed-effect regression correlating the visual analog scale test (VAST) results with the velocity changes observed during the dynamic adjusted lane test (DALT). The observed continuum establishes interplay between each insole treatment's perceived surface roughness and corresponding gait adaptability.*

By sourcing measures of perceived surface roughness provided in the VAST and data on gait adjustment velocities provided in the DALT, a combinatory polynomial mixed-effect regression was produced to reflect the relationship between variables (Figure 16). As a result, a quadratic relationship relating gait adjustment in terms of percent velocity decrease with the corresponding VAS scores reported during the VAST can be seen, governed by the formula, $y = 0.3084x^2 - 3.0352x + 16.904$. The y-axis (VAS score) captures all possible values on the administered VAS scale that could have been reported, allowing for an extrapolation of the results to determine the corresponding %ΔV metric for all possible ratings of insole surface roughness.

Similar to the BAST, another continuum emerges from the data indicating that intermediate levels of perceived roughness are a viable option for enhancing lower limb kinematics and gait adaptability. Although these continuums (Figure 12,16) report the performative enhancements of intermediate levels of perceived surface roughness when compared to the lower end of the spectrum of VAS scores, it is also important to note that performance is eventually inhibited at the higher end of the VAS spectrum as well, indicating a goldilocks range for the efficacy of textured insole technology. This information could be extremely useful when optimizing footwear technology to maximize locomotor coordination within the wearer. Further studies and additional subjects may be needed to determine if this polynomial relationship remains constant over time or if surface roughness potentially modulates unforeseen factors of gait adaptation not shown in the current data.

CHAPTER 4

DISCUSSION

4.1 Overview of Study Application

Although both DTA tasks (DALT and DAST) provide valuable information on the effects of insole treatments on individual cognitive outputs, they differ in their application to overall performance. For example, the DAST measures an individual's ability to dynamically react to auditory stimuli and respond accordingly through verbal responses. In this case, the administered auditory stimuli function as a task perturbation that must be addressed by properly synthesizing the corresponding verbal response. Conversely, the DALT assesses an individual's ability to react to a visual perturbation, taking the form of a narrowed lane intervention, that forces subjects to adapt their gait through the execution of proper motor responses.

Therefore, both subtasks of the DTA are measures of the cognitive efficiency employed by the individual to carry out appropriate dynamic responses as defined by the reaction time needed to evaluate the task interventions. By analyzing performance adjustments in response to the auditory stimuli presented in the DAST and the visual stimuli presented in the DALT, the DTA is able to demonstrate a holistic representation of the ability of textured insoles to modulate locomotor learning during dynamic tasks. This holistic representation of audiovisual perturbation response was developed intentionally to incorporate the various cues repeatedly administered during athletic performance.

For example, in the context of association football, players are required to maintain a constant stream of communication with teammates. Whether it is calling for the ball, notifying teammates of incoming defenders, or listening to instructions from sideline coaches, the player is constantly required to demonstrate a high level of auditory acuity in order to function at full capacity. If a textured insole intervention could significantly improve reaction time in this domain, it would be seen in the DAST, as subjects were timed for efficiency of response to auditory cues.

Similarly, association football players must constantly make motor adjustments to adapt to visual perturbations as well. Visual perturbations in this context are abundant. For example, minute perturbations resulting in changes in the playing surface must be accounted for to maintain proper performance. A more concrete visual perturbation a player encounters would be an opposing defender. This scenario undoubtedly requires moderate to extreme gait adjustments to circumvent the perturbing forces of a defenseman. Nevertheless, if a textured insole intervention were a viable method for improving reaction time in this domain, it would be seen in the DALT, as subjects reactively responded to visual changes in their environment by adjusting gait to produce the appropriate motor responses.

As mentioned previously, the DAST will fall outside the scope of this program of work, and results regarding the DAST subtask will be analyzed and discussed at a later date to supplement this dissertation. Consequently, the discussion of any mechanisms underlying performative variations resulting from the textured insole interventions will be in the context of adaptation to visual perturbations necessitating motor adjustments in lower limb kinematics and overall gait. As reflected previous discourse in the introduction, biomechanical adjustments observed during testing served as a proxy for cognitive reaction time in response to the narrowed lane perturbations introduced in the DALT. Therefore, DALT analyses will serve as a thorough representation of the locomotor interface responsible for incorporating sensory information from insole treatments and processing visual perturbations in the dynamic testing environment.

The results of the DALT build on previous literature that has shown that the input of additional sensory stimuli to the plantar surface is a viable method for increasing cognitive acuity and thereby inducing elevated biomechanical efficiency as a downstream biproduct (Miranda et al., 2016; Rafiei et al., 2023). Additionally, the current study lends support to preliminary data that shows that textured insole technologies are an evidence-based mechanism for improving motor task performance, proprioception, and postural stability in both healthy and diseased populations (Corbin et al., 2007; Dixon et al., 2014; Hatton et al., 2019; Waddington & Adams, 2000, 2003). Furthermore, the increased efficiency during gait adaptation reported in the DALT is also highly aligned with studies that have reported performative improvements within a sports context. Specifically, these data support previous studies that have confirmed the ability of textured insoles to improve proprioception and lower limb kinematics in athletes (Bapirzadeh et al., 2014; Hasan et al., 2016; Waddington & Adams, 2000, 2003). Similar studies that have shown increased efficiency during sports-related dynamic tasks are also reinforced by the DALT data, which indicates that sensory-enhancing insoles can and do affect biomechanical performance as a result of enhanced cognition (Hasan et al., 2016; Miranda et al., 2016).

4.2 Relationship Between Perception and Performance

The statistically significant differences reported between all insole treatments in the VAST, aside from the I2, I3 comparison (Figure 9), demonstrate a clear link between the addition of insole texture and perceived surface roughness. However, no linear relationship can be concluded here between the level of texture and perceived roughness, as such metrics of increased and decreased texture are too ambiguous to quantify and correlate. Therefore, VAS scores represent a standalone metric that quantifies the fairly evident fact that adding any insole texture increases perceived insole roughness. That said, the fact that all administered insole treatments evoked a visually unique perceptual profile in terms of surface roughness was undoubtedly beneficial to the breadth of this analysis.

The current study builds off of previous work done in the adidas-ASU Center for Engagement Science, involving a similar set of tests carried out in order to provide a relationship between performative capability and perceived comfort while instrumented with footwear delivering varying intensities of vibrational noise to the upper shoe region (Rafiei et al., 2023). Although it may seem that employing a VAS scale rating system of lowest to highest perceived comfort as opposed to surface roughness would be a more valuable system for delivering footwear design recommendations, this was deemed suboptimal for achieving the aims of the current study. Perceived comfort has proved too subjective of a rating scale, leading to a looser interpretation of results, whereas subject-reported surface roughness scores allow for a more constrained analysis. Essentially, different subjects will provide a wide variation in responses to answer the question of which insole treatment is most comfortable for them. On the other hand, surface roughness offers guidelines for a more universally perceived scale of sensory intensity.

Rafiei et al., (2023) reported a strong non-linear relationship between perceived comfort and auditory reaction time that was in all aspects contradictory to the relationships we observed between perceived roughness and mediolateral postural sway (Figure 12) and between perceived roughness and gait adaptation velocity (Figure 16) shown in the current study. This stark difference lies in the fact that Rafiei et al. (2023) concluded that the lowest and highest extremes of perceived comfort, as reported through their respective VAS test, were associated with higher levels of cognitive and biomechanical performance when compared to intermediate recorded VAS scores. Conversely, the continuums produced in the current work clearly show that intermediate VAS scores were associated with higher performance levels during both physical task assessments. These incongruent results between Rafiei et al., (2023) and the current study do not question the validity of either research work; instead, they represent the nuances of each experimental procedure, specifically the variation in terminology employed during the respective VAS evaluations (perceived surface roughness vs. perceived comfort).

However, more than anything, the data disparity shows that the addition of stimuli to the dorsal foot regions, as seen in Rafiei et al., (2023), is not directly comparable to similar treatments targeting stimulation to the sole of the foot. In fact, given the contradictory effects seen during these methods of stimulation, it is likely that the receptors on the dorsal region of the foot incorporate additional stimuli through an entirely different mechanism compared to the afferent areas of the foot sole. Despite this suggested incompatibility, Rafiei et al., (2023) and the current study do agree in the conclusion that the addition of sensory stimuli via a footwear-focused cutaneous augmentation device does induce an altered emotional response as recorded through subject-reported VAS scores regardless of the terminology used on those assessments. Future studies may be useful in minimizing the confounding factors that result from subjective responses associated with variations in VAS prompts and further refining the emotional response quantification methods employed in our lab's work.

The measured correlation between VAST performance and performance during the BAST (Figure 12) and DALT (Figure 16) provide interesting insights into the possibility of optimizing the roughness of textured insole augmentation devices. This concept seems counterintuitive and challenges the idea that any form of insole surface perturbation would negatively affect user experience. Although minimal insole surface roughness may represent an ideal footwear design for those seeking more streamlined casual comfort, the current study's results show that this may not be the best approach for optimizing attentional response and locomotor coordination during motor tasks.

Results reported in the VAST defined insole treatments into three distinct groupings concerning statistical significance, the first being the I1 insole treatment, which represented the lowest end of the perceived surface roughness spectrum and rightfully so, given its lack of any additional texture. Due to the absence of statistically significant VAS recordings in the I2 and I3 comparison, these treatment groups can be unionized into the second grouping evaluated in this study, representing intermediate surface roughness scores. Finally, the third grouping, defined by the highest levels of perceived surface roughness reported during the VAST, is captured by data attributed to the I4 treatment.

When correlating the VAST results with the static balance performance observed during the BAST (Figure 11), it is shown that our second defined grouping of intermediate perceived surface roughness represented by the I2 and I3 conditions induced statistically enhanced stability along the mediolateral axis. This result is further supported when mediolateral sway is directly visualized as a function of raw VAS scores, producing a continuum curve correlating intermediate roughness with optimized stability (Figure 12). By minimizing this curve function, it is shown that an optimized BAST performance can be achieved through a textured treatment that incorporates a perceived surface roughness VAS score of 5.86, corresponding to a GRMS of only 0.05 m/s^2. By comparing this GRMS to the mean GRMS of the I1 condition, 0.13 m/s^2, it is shown that VAS optimization can reduce mediolateral sway in the baseline control condition by up to 34%.

Similarly, when correlating the VAST results with the dynamic performance seen in the DALT (Figure 15), the second defined grouping of intermediate VAS scores again shows a performance-enhancing effect. Although mean reductions in percent velocity decrease were objectively minimized in both the I2 and I3 conditions compared to the I1 control, only the I3 treatment reached significance. These results are preserved by a separate analysis correlating the percent velocity decrease experienced during the DALT directly to subject-reported VAS scores (Figure 16) through another continuum curve. According to this functional relationship, it is suggested that optimal gait adaptability during the DALT would be achieved through a textured intervention delivering a 5.86 perceived roughness VAS score, resulting in only a 9.44% reduction in velocity when adapting to the regularly introduced perturbations. Comparing this result to the mean percent velocity reduction seen during DALT performance under the I1 condition which induced a 15.60% velocity decrease, it is shown that the incorporation of optimized texture has the capacity to induce up to a 6% increase in adaptability and running economy when compared to a baseline control.

In summary, these findings are promising because the BAST and DALT show that textured insole treatments outperformed traditional insoles throughout all facets of experimentation. Results specifically indicate that being able to achieve an optimal VAS score that corresponds to the minimization of the perception-performance continuums (Figure 15, 16) allows enhancements of up to 34% in static postural control (BAST) and up to 6% in dynamic adaptability (DALT). Although it is important to note that intermediate levels of texture outperformed the baseline control I1 treatment, it is just as important to note that when VAS scores reached the higher end of the perceived surface roughness spectrum, performance was once again inhibited.

These findings suggest that low VAS scores reported during I1 performance went perceptually unnoticed during task evaluation, resulting in baseline performance. In contrast, the increased levels of systematic noise produced by the textured insole interventions seemed to reach a certain perceptual threshold that demanded conscious balance control. In terms of the current study, this information can be extrapolated to suggest that intermediate levels of perceived surface roughness, seen predominantly during the I2 and I3 treatments, surpassed this threshold, triggering a heightened level of attentional focus exhibited by conscious postural regulation. Conversely, lower VAS scores reported under the I1 condition were potentially inadequate to surpass this supposed sensory threshold and, therefore, created no observable effect on baseline performance. However, the nature of the continuums further imposes that once perceived roughness levels became too high, performance was once again inhibited.

Logically speaking, this is perhaps expected as at a certain point another sensory threshold is passed where the addition of insole surface roughness becomes perturbing and even painful, thus creating performance-inhibiting noise instead of focused proprioceptive control. Underlying neural pathways involved in these phenomena are not defined in the current literature; however, further discussion in the current program of work will allude to a potential relationship between the sensorimotor phenomenon of conscious balance control and the specific neural activity underlying enhanced performance during externally directed attentional focus.

4.3 Potential Mechanisms Underlying Performative Improvement

4.3.1 Directed Attentional Focus

To reiterate a sentiment proposed during the introduction of the current program of work: It has been shown that textured insoles do have a significant effect on performance; however, the mechanism by which this effect is produced is still not yet fully understood.

Given previous research on the matter, one potential mechanism that can be reasonably considered involves the cognitive impact of directed attentional focus (DAF). DAF refers to a system of response that functions to register cognitive cues relative to the subject's locus of attention. In the case of DAF, cognitive cues arise either from an individual's environment (external) or from within the individual themselves (internal). External cues can arise from any number of environmental changes that an individual perceives, such as variations in playing surface or weather. On the other hand, internal cues are attributed to directing an individual's locus of attention inward towards the proprioceptive awareness of their body's position in space.

Significant bouts of research have been dedicated to leveraging DAF for performative enhancements. These efforts have focused explicitly on uncovering the optimal cueing strategy for producing desired behavioral outputs such as heightened cognitive acuity. Through experimentation with various combinations of internal and external cueing strategies, as well as evaluation of each cueing method in isolation from the other, the current literature has found that externally DAF produces more significant degrees of enhancement during motor task performance when compared to the method of internally DAF (Becker & Fairbrother, 2019; Song, 2019). This means that when an individual receives cognitive cues outside of their own proprioceptive field (external cues), they will innately be able to achieve higher levels of performance during motor tasks, as opposed to if they were to focus on their body's position or mechanics during the task completion process.

The mechanism by which DAF enhances performance via textured insoles assumes that the tested insoles would shift an individual's locus of attention towards the area of treatment (their feet) during task completion. Initially, one would think that this is an example of internally DAF, and indeed, it has been shown that shifting the locus of attention towards foot-centered proprioception presents an internal cueing mechanism, thereby inhibiting motor performance (Wulf et al., 1998). However, during the psychophysical assessment administered during the DALT, the primary metric of analysis is the subject's locomotor adaptation to the narrowed lane perturbations. Therefore, the task at hand is inherently a cognitive assessment of reaction time as opposed to a motor assessment of biomechanical performance.

Given this rationalization, it can be inferred that since the task is carried out primarily through the brain's core processing functionality, then shifting the locus of attention toward the external perception of the feet could be considered an external cueing strategy. If the logistical reasoning of this mechanism tracks, the additional stimuli delivered to the subject via the textured insole treatment would provide an externally directed attentional response. The textured insole treatment would effectively enhance performance during the DALT via externally DAF by cognitively cueing the individual's attention towards an external region outside of the body's core computational functionality. Whether externally DAF can be accepted as a means for inducing enhanced performance during the DALT is yet to be confirmed; however, the theory certainly warrants further testing.

4.3.2 Alpha/Beta Band Oscillations

Although the proposed mechanism of DAF may provide key insights into how the somatosensory experience of the foot sole is modulated by textured materials, a clearer picture could potentially arise by taking a closer look at the more quantifiable metrics of nervous function. The brain's rhythmic electrical response system, namely alpha and beta band activity, has captured the focus of a broad sector of sensorimotor research endeavors due to the ability of these neural activity patterns to align with an individual's physiological state (Klimesch, 2012). Moreover, the ever-changing oscillatory state of sinusoidal waves representative of alpha and beta band activation and suppression can be readily observed through non-invasive imaging techniques such as functional magnetic resonance imaging (fMRI), electroencephalography (EEG), and magnetoencephalography (MEG) (Abreu et al., 2018; Brinkman et al., 2014).

A study by Brinkman et al. (2014), employing MEG for the analysis of neural oscillatory patterns, showed alpha and beta band activity was quantifiably modulated by an individual's mental stimulation of goal-directed movements. The study suggests that data acquired on neural activity can serve as a direct link for interpreting the various markers preceding the body's dynamic physiological response, which was shown to be significantly mediated by cognitive intention even before biomechanical action is taken. This indicates that neural imaging of alpha and beta band activity can be a powerful precursor to physically demanding goal-directed actions and overall psychophysical interaction. With this additional context, an evidence-based method of analyzing the oscillations of neural patterns and how they relate to organized motor movements could provide a means of describing the mechanisms of sensorimotor interaction during a textured insole treatment.

Luckily, this method of analysis has been previously employed in a context aligned with observing the neural effects of additional sensory stimulus. The study in question, done by Kim et al. (2020), successfully showed that the variance in alpha and beta band oscillations within the brain is highly coordinated with the somatosensory response of vibrotactile stimulus within fast-acting mechanoreceptors. Although the additional stimulus provided here arises from a vibrotactile input source, the results are still highly comparable to the supposed effects of texture in the same context, given that both stimulation methods are mechanical in nature. Additionally, the locus of stimulation on each subject was the left and right tips of the subject's index fingers, mainly targeting responses from fast-adapting cutaneous mechanoreceptors within this region. Fast-adapting mechanoreceptors are also the main sensory receptor class lining the glabrous skin of the foot sole (Hennig & Sterzing, 2009; Kennedy & Inglis, 2002). This specific afferent class of receptors on the foot sole has been shown to be essential for providing cutaneous feedback for lower limb proprioception during a similar study that also measured the performative response of vibrotactile stimuli (Mildren & Bent, 2016).

By analyzing these studies from Kim et al. (2020) and Mildren & Bent, (2016), a fuller picture of how neural activity modulates lower limb kinematics can be jointly interpreted. The exact nature of alpha and beta band oscillations and how they underly different cognitive and performative states can be deciphered by diving deeper as well. For example, Kim et al. (2020) showed that alpha and beta activity observed in the primary sensorimotor cortex (SMI) and the secondary somatosensory cortex (SII) oscillated in accordance with the application of vibrotactile stimuli. Specifically, the study referenced alpha power reductions observed upon administration of the stimuli. Alpha band suppression, to this degree, has been correlated to the activation and facilitation of sensory information processing during motor tasks (Kim et al., 2020; Neuper et al., 2006; Pfurtscheller et al., 1996). As for beta band activity, Kim et al. (2020) showed oscillatory readings to be largely suppressed in the SII region, a neural process that underlies the efficient performance of high-order functions such as mentally demanding tasks with significant attentional demands (T. L. Chen et al., 2008; Kim et al., 2020; Mima et al., 1998).

These aforementioned studies, primarily Kim et al. (2020) and Mildren & Bent, (2016), link together to show how neural responses are affected by an added stimulus and how oscillations of the brain might be modulated during different biomechanical and performance-based tasks involving decision making and attentional focus. By extrapolating these results to their application in the current program of work, this section of discussion can be summarized in a few key points. Firstly, alpha and beta band activity patterns are similarly modulated during the cognitive visualization and biomechanical performance of motor tasks (Brinkman et al., 2014). Secondly, the addition of mechanical stimulus has been shown to have a comparable effect on neural processing during the targeted application of vibrotactile stimuli to fast-adapting mechanoreceptors (Kim et al., 2020). Finally, Mildren & Bent, (2016) showed that the addition of vibrotactile stimuli to fast-adapting mechanoreceptors on the foot facilitates lower limb proprioception. With these three key points, it can be inferred that the addition of mechanical stimulus to the mechanoreceptive regions of the foot sole modulates the oscillatory patterns of alpha and beta band activity within the brain, enhancing the cognitive visualization of motor tasks. This ultimately leads to an enhanced biomechanical output resulting from faciliatory neural processes that drive improvements in lower limb proprioception through a traditional stimulus-driven bottom-up effect.

4.4 Proposed Stimulus-Driven Effect for Texture-Enhanced Performance

Mechanisms involving the concepts of externally DAF and the presence of perception-mediated neural signaling have been proposed to derive a basis for the process by which additional sensory stimuli are incorporated for improved performance. However, it may be useful to consider that the presence of alpha and beta band responses during motor movement planning is not mutually exclusive to the phenomenon of externally DAF. In fact, both of these mechanistic domains may actually merge to provide an explanation for the holistic expression of psychophysical interactions that arises from the perceived sensation of textured insoles. To summarize how this complex interaction could come to fruition, a bottom-up effect of stimulus-driven sensory processing is proposed:

Additional stimulus is provided by textured insoles → externally DAF is induced → alpha and beta band neural activity is modulated → cognitive processing is enhanced → biomechanical performance is improved.

This is a lofty assumption at first glance; however, the proposed mechanism is entirely founded in empirical evidence produced across multiple studies.

4.4.1 Textured Insoles Induce Externally Directed Attentional Focus

Firstly, it is postulated that the perceived sensation of texture induces externally DAF. It has been previously explained in this program of work that shifting the locus of attention towards the feet during complex gait adaptation is best aligned with the principles of externally DAF and, thus, is a performance-promoting method of task engagement. This viewpoint is supported by the *Constrained Action Hypothesis,* which attributes the benefits of externally DAF to the disruption of autonomous bodily processes that occurs when internally DAF is employed to precisely control specific body segments (McNevin et al., 2003; Wulf et al., 1998, 2001). During the DALT, the locomotor adaptation that must occur in preparation for traversing the narrowed lane interventions is a primarily autonomous function of internal cognition. Therefore, shifting focus from the internal locus of cognitive processing towards the feet through textured materials, would allow for more efficient and autonomous locomotor adaptation via externally DAF.

This process also empirically tracks with the rest of the proposed bottom-up mechanism of textured stimulus incorporation because the perceived sensation of mechanical stimuli has been repeatedly associated with the other sequential components of the bottom-up effect. For example, it has been shown that the addition of tactile stimuli to fast-adapting mechanoreceptors is associated with neural oscillations of alpha and beta band activity that have been recorded during stages of elevated mental acuity and motor coordination (Brinkman et al., 2014; Chota et al., 2023; Kenny et al., 2020; Kim et al., 2020). Similarly, a vast amount of research has supported the use of textured insoles for their ability to modulate biomechanical performance, proprioception, and overall postural stability (Hasan et al., 2016; Mildren & Bent, 2016; Nurse et al., 2005; Orth et al., 2013; Waddington & Adams, 2000, 2003). With this well-established interconnectivity and validated rationale for the ability of textured insoles to induce externally DAF, the first phase of our proposed mechanism can be reasonably substantiated:

Additional stimulus is provided by textured insoles → externally DAF is induced

4.4.2 Externally Directed Focus Modulates Neural Activity Patterns

Moving onto the next component part of the proposed mechanism for texture-enhanced performance, it must now be demonstrated that externally DAF induces oscillatory patterns associated with improved cognition and biomechanical performance. The scientific consensus that externally DAF facilitates locomotor learning during athletic endeavors (Becker & Fairbrother, 2019; Song, 2019) is a highly advantageous supporting piece of evidence for describing the texture-enhanced performance seen during the DALT. Fortunately, these findings have warranted further exploration into the neural phenomenon underlying their results. A specific study in which the contrasting neural effects of internally and externally directed attentional focus are compared can be seen in Compton et al. (2019), during a study in which EEG observed alpha band oscillations were correlated with varying degrees of task focus. Compton et al. (2019) successfully replicated previous findings that suggested that increases in EEG alpha power are readily apparent during task performance, in which the subject reports diminished focus or mind-wandering. The results showed that increases in alpha power are a reliable neural marker for the mind-wandering effect associated with inward-directed cognition seen during internally DAF (Compton et al., 2019). Compton et al. (2019) also claims the contrasting effect to be equally substantiated in that the same neural markers observed during mind-wandering are significantly suppressed during externally directed cognition.

Magosso et al. (2019), a similar study that also explored the attentional modulation of neural activity by means of EEG, confirms this sentiment through observation of the same alpha suppression event during tasks that employed externally DAF (Magosso et al., 2019). Furthermore, Magosso et al. (2019) emphasizes the finely tuned modulatory effects of externally DAF during mixed visual-cognitive tests through the use of virtual reality testing, during which subjects were presented with visually-driven arithmetic assessments and instructed to internally compute proper responses. The results showed alpha band activity to be significantly reduced during these tasks, further emphasizing the utility of externally DAF during visually dominated cognitive evaluations (Magosso et al., 2019). These findings are specifically compelling when related back to the current study as the DALT is by all accounts a visually dominated cognitive assessment, comparable to the visually driven virtual reality arithmetic assessments employed in Magosso et al. (2019), as it requires the subject to visually identify perturbations that are autonomously adjusted for through locomotor adaptations. The comparative treatments described here add to the mounting evidence that a textured insole intervention would be effective in inducing externally DAF by visually cueing the individual away from the autonomous cognitive processing carried out during tests that overlay physical and mental factors such as arithmetic evaluations or induced gait adjustment assessments.

Compton et al. (2019) and Magosso et al. (2019) provide sufficient evidence to support the fact that the reallocation of the locus of attention to external stimuli during externally DAF is associated with alpha band oscillations that are observed during sensorimotor tasks in which subjects experience a heightened level of cognition and performance. However, the activity within the beta band observed during subject performance is also highly important to the proposed texture-induced performance mechanism. The previously addressed Brinkman et al. (2014) study sheds light on this facet of performance-based neural marking by demonstrating that the suppression of beta band oscillations within sensorimotor regions of the brain facilitates neuronal populations that participate in processing various movement parameters such as speed, direction, and coordination. Additionally, the results showed that this process is undertaken to modulate task performance whether the task is physically completed or cognitively imagined (Brinkman et al., 2014). This point is particularly interesting for our specific study application because it emphasizes the complex interplay that underlies sensorimotor communication during a psychophysical assessment akin to the DALT. Identical neural activity observed during both real and imagined movements in combination with the previously established sentiment that the addition of mechanical stimuli modulates these particular signaling markers provides empirical evidence for the proposed bottom-up mechanism.

Similar decreases in rhythmic beta band activity to those seen in Brinkman et al. (2014) have also been observed as a result of targeted tactile noise stimulation, an administered treatment that is highly comparable to the application of textured materials (Chota et al., 2023). In fact, applied tactile stimulation, organized movement preparation, and motor task execution have all been observed during instances of measured power decreases in beta band oscillation (Chota et al., 2023; Parkkonen et al., 2015; Pfurtscheller et al., 1996). Studies have categorized this degree of beta band suppression as representative of neuronal excitation within the somatosensory cortex, allowing for more efficient processing of external information during the stimulus-action feedback loop employed to correlate perception and biomechanical performance (Cassim et al., 2001; Chota et al., 2023).

By correlating neural signatures of alpha and beta band activity to the application of tactile stimulation and associating this response with enhanced cognition and motor movements, the previous literature stands in full support of the proposed mechanism by which textured materials enhance overall performance. By providing a link between externally DAF and neural markers that are aligned with elevated cognition and motor assessment, the final pieces of the initially postulated bottom-up effect can be synthesized:

Externally DAF is induced → alpha and beta band neural activity is modulated → cognitive processing is enhanced → biomechanical performance is improved

CHAPTER 5

CONCLUSION

5.1 Study Summary

By analyzing the effect of sensory augmentation through a textured insole intervention, the current study provides new insights into the complex interplay that exists between perception and action during dynamic task completion. Subject-reported perceived surface roughness was recorded during basic visual analog testing, static postural control was quantified through mediolateral sway, and relative gait adaptation velocity was measured through a protocol that introduced confined running spaces requiring appropriate locomotor adjustments. The primary outcome of the combinatory results acquired through these tests was a distinct pattern outlining the non-linear relationship between perceived surface roughness and gait adaptation velocity. Data showing diminished performance observed at the extreme ends of the VAS spectrum and enhanced stability and gait adaptability shown during treatments associated with intermediate VAS recordings supports a new model of evidence-based footwear development that incorporates the addition of texture. This correlation emphasizes the importance of the foot sole in sensory information processing and provides a strong case for the inclusion of footwear designs that leverage the foot's sensory properties for increasing cutaneous feedback and improving performance.

Furthermore, the current study also proposes a holistic approach aimed at describing the bottom-up stimulus-driven mechanism by which texture may affect cognitive and biomechanical capabilities. This potential mechanism links the validated concepts of multiple studies aimed at analyzing the effects of texture, externally directed cognition, and various neural activity patterns to elevated performance during the completion of static control and dynamic tasks with significant visual demands. Data acquired during dynamic testing demonstrates some of the earliest evidence advocating for the ability of textured insoles to enhance locomotor adaptation, whereas results regarding improvements during standing bilateral balance are in harmony with the current literature in this research domain. The discussion also provides a unique view on the potential underlying processes influencing the relationship between textured materials, neural activity, and enhanced performance. The sum of all effects observed during this study shows how the body's attentional response is correlated to biomechanical performance during static balance and locomotor adaptation and how these processes are potentially modulated by the additional somatosensory stimuli provided by textured insoles. Applications of these findings within a young, healthy population show that textured materials are also a viable method for cutaneous augmentation in the average population and in the realm of athletic performance, building on the current body of research that has primarily emphasized the role of textured insoles within diseased and elderly subset samples.

5.2 Future Directions

Although the results reported so far are promising and in alignment with the specific aims of this study's research mission, further work is necessary to provide a more comprehensive review of the concepts involving texture-enhanced performance. A sample size of 10 participants was used to represent this protocol's preliminary results; however, a complete sample of 20 participants will be recruited and evaluated before the current study is concluded. If significant differences in balance and gait adaptation velocity do occur as a result of the varying insole conditions, then the complete sample size and subsequent analysis will show this information objectively, allowing for a more definitive representation of results.

Additionally, analysis of the other experimental tests conducted in unison with the BAST, DALT, and VAST will also be completed and included with the current study to provide a fuller picture of the specific mechanisms affected by the textured insole treatments. Results from the currently omitted ankle proprioception tests will shed light on how the insole treatments affect static parameters of postural discrimination, while results from the DAST will provide information on texture-induced reaction time to the occurrence of an auditory stimulus. These results will reinforce current studies and future work that look to employ new methods of cutaneous augmentation through footwear designs aimed at improving sensorimotor processing during static and dynamic tasks involving high mental and physical loads.

Future work needed to supplement the claims made during this report includes a set of studies positioned to uncover the optimal VAS methodology. Several different VAS scales for rating numerous subjective factors, such as pain, comfort, happiness, and sadness, have all been employed in hopes of achieving a validated emotional response quantification. Methods involving subject-reported emotion will always have a significant grey area due to individual variations in perception; however, further research could shed light on an optimal strategy for limiting this effect.

Finally, the proposed effect aimed at describing the underlying mechanism of texture-enhanced performance, although rooted in empirical evidence, requires further studies to ascertain its validity. Future studies involving the measurement of neural signaling during task completion while instrumented with a textured intervention are required to confirm their efficacy for modulating alpha and beta band activity within the brain. Although this phenomenon can be theorized, given its established effect during vibrotactile stimuli, textured insoles present a different treatment approach, which may yield different results. Similarly, a novel experimental design would be needed to establish the proposed cause-and-effect relationship between textured insoles and externally directed attentional focus. Data acquisition involving the previously mentioned neural markers could provide a stronger foundation for this principle, given the established relationship of externally directed focus and alpha and beta band signal modulation.

Overall, textured insoles provide a passive and inexpensive means of enhancing static and dynamic task execution. For being a passive and inexpensive method of sensory augmentation, textured insoles set themselves apart by delivering performative returns that far surpass the labor cost needed to implement them. Given that sensory perception is a universal constant of the human condition, the technology proposed in this study has the potential to restore stability in those who have lost it due to age or disease as well as enhance coordination in the average population or even competitive athletes alike.

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APPENDIX A

INSTITUTIONAL REVIEW BOARD APPROVAL

APPROVAL: EXPEDITED REVIEW

Aurel Coza
KE-CESP: Center for Engagement Science
Aurel.Coza@asu.edu

Dear Aurel Coza:

On 3/2/2024 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Methodologies Toolbox for Biomechanical Performance, Cognitive Acuity, and Proprioceptive Awareness
Investigator:	Aurel Coza
IRB ID:	STUDY00019610
Category of review:	4,7
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• IRB Social Behavioral Protocol_03_04_2024.docx, Category: IRB Protocol; • IRB_Recruitment_Questionaire.pdf, Category: Screening forms; • IRB_Subject_Emails_03_04_2024.pdf, Category: Recruitment Materials; • PAR-Q, Category: Screening forms; • Participant instructions .pdf, Category: Participant materials (specific directions for them); • Textured Insole Study Consent Form_03_04_2024.docx.pdf, Category: Consent Form;

The IRB approved the protocol from 3/2/2024 to 3/1/2025 inclusive. Three weeks before 3/1/2025 you are to submit a completed Continuing Review application and required attachments to request continuing approval or closure.

If continuing review approval is not granted before the expiration date of 3/1/2025 approval of this protocol expires on that date. When consent is appropriate, you must use final, watermarked versions available under the "Documents" tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc:

Christopher Boll
Justin Maldonado
Aurel Coza