How does emotion affect the way we walk?

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Gait, the way that human beings walk, is a large component and indicator of health in both young and older adults. Gait has been used in the past to identify injury and fall risk, progression of diseases and is used as a measure indicative of overall health in adults. Many factors affect the gait cycle including age, disease, injury, and even mood disorders such as anxiety and depression. This study aims to investigate how moods themselves or *emotions* affect gait to understand whether everyday emotions may impact gait and whether emotions could be potential confounds in gait analysis. Using the 5-factor model of gait, this study aimed to categorize how gait parameters changed when feeling the emotions of happy, excitement, anger, fear, and sadness. It was hypothesized that emotions of happy, excitement, and anger would result in increased pace while emotions of fear and sadness would result in decreased pace but increased variability when compared to a neutral condition. Secondary analysis of how gait is correlated with changes in the pleasure, arousal and dominance dimensions of emotions were also conducted to map changes in gait to changes in underlying dimensions of emotions rather than specific discrete categories. It was hypothesized that pleasure, arousal, and dominance would be positively correlated with the pace domain and negatively correlated with the variability domain. The study examined 26 healthy young adults and 14 of which were selected for further analysis. Emotions were elicited using virtual reality and immersive video. The results showed that only sadness of all emotion conditions was different from other emotions and the neutral condition. During the sadness condition, participants walked with reduced step length, gait speed (pace domain) and with increased step time and stance time (rhythm domain) when compared to all other emotion conditions including the neutral condition. No changes were observed in other domains of variability and postural control. Correlation tests showed that it was mainly the dimensions of pleasure and dominance that were associated with changes in gait patterns, resulting in positive correlation with step length and gait velocity. Arousal showed a weak negative correlated with stride velocity variability and no other correlations were observed. Overall, these results indicate that while everyday emotions may play some role in influencing gait, it is really the emotion of sadness, that plays a large role in modulating gait; perhaps this emotion should be taken into account as a potential confound for future gait analysis.

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List of Abbreviations

PFC – Prefrontal Cortex

M1 – Primary Motor Cortex

S1/S2 – Primary / Secondary Somatosensory Cortex

BG – Basal Ganglia

PN – Pontine Nuclei

CPG – Central Pattern Generator

PD – Parkinson’s Disease

VR – Virtual Reality

PAD – Pleasure Arousal and Dominance

5HT – Serotonin

DA – Dopamine

NE – Adrenaline

IAPS – International Affective Picture System

IADS – International Digitalized Sound System

EDA – Electrodermal Activity

SAM – Self Assessment Manikin

mDES – Modified Differential Emotions Scale

1.0 Introduction

They way that we walk, or human gait, is the result of the simultaneous, bi-directional interactions between the motor system of the brain and other cortical and sub-cortical structures (Deligianni et al., 2019; Takakusaki, 2013). Due to this exceptional nature, the analysis of gait has been integral for clinicians and researchers in diagnosis of disease; it serves as an important tool for tracking many different indicators of health and progression of neurological disorders (Chen et al., 2016; Ehgoetz Martens et al., 2014). When healthy gait is impaired as a result of disease or injury, there is an associated increase in the risk of falls, disability and overall loss of quality of life (Mancini et al., 2019). Previous studies have shown that mood disorders such as anxiety and depression can impair gait (Ehgoetz Martens et al., 2018). While the literature of mood disorders and its associated impact on gait has been investigated, few studies have looked at the role of emotions in gait, and how changes in an emotional state causes changes in observed gait characteristics. It is imperative to consider the changes in gait characteristics that arise from emotional states; as these changes can possibly confound the gait characteristics observed in both healthy and non-healthy populations, leading to potential false characterizations of gait characteristics.

1.1 Human Gait

Human gait is incredibly complex. Its neural control consists of intertwined higher order neural structures that relay information to spinal regions and ultimately affect the cyclic and rhythmic movement of skeletal muscle (Deligianni et al., 2019; Takakusaki, 2013). These neural centers include cortical structures such as the Prefrontal Cortex (PFC), the primary motor cortex (M1), primary/secondary somatosensory cortex (S1/S2) as well as sub-cortical brain regions such as the cerebellum, basal ganglia (BG), Pontine Nuclei (PN), and thalamus. All these structures (alongside others) contribute to the overall gait cycle (Deligianni et al., 2019). Gait, being a goal directed movement, requires some form of external or internal stimulus for initiation (Takakusaki, 2013). Take the example of a person who is thirsty and sees water at a nearby table. Both external (water source) and internal (thirst) stimuli drive the person to initiate gait and move towards the object. This stimulus starts the cascade of functions termed the "Volitional-Cognitive" reference (see Figure 1), which originates from the cerebral cortex alongside previously mentioned cortical structures (PFC, M1, S1/S2) and travel down towards the spinal cord (Takakusaki, 2013). Simultaneously, subcortical regions and structures like the BG, PN and cerebellum modulate this flow of neural activity as it travels beyond the midbrain and reaches the spinal cord (Takakusaki, 2013). Here, in the spinal cord, is where the basic automatic rhythmic pattern of gait is generated (Guertin, 2013). Like pedals on a bicycle, the spinal cord contains specific interneuron regions called half-centers or central pattern generators (CPGs) that controls the reciprocal flexion and extension activity of the muscles that create the movement of gait (namely the flexor and extensor activity of the lower limbs). As one pedal rises--the other falls, or in the case of gait, when the flexors are activated, the extensors are inhibited and vice-versa. This cyclic motion allows gait to proceed in this automatic, rhythmic pattern even in the absence of higher order cortical input as found in decerebrate animal studies (Guertin, 2013; Takakusaki, 2013).

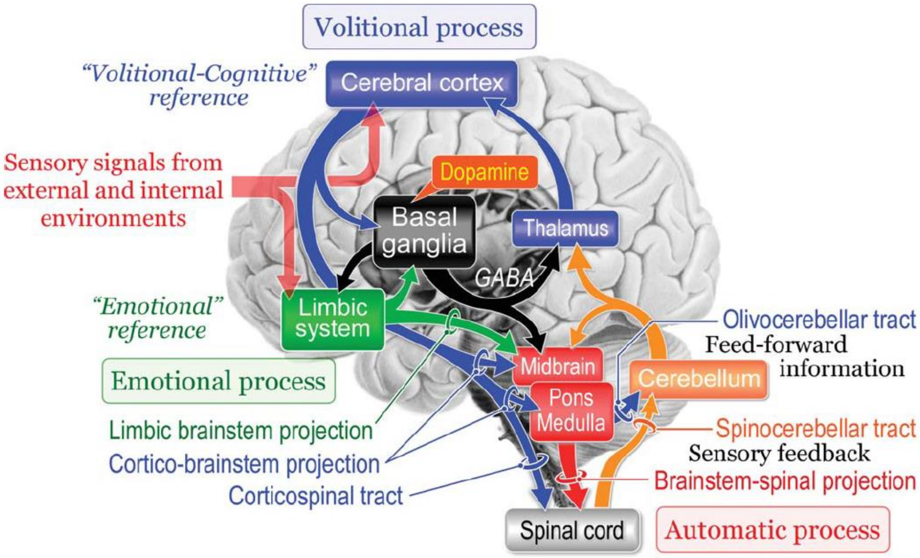

Figure 1 Shows the main pathways of the volitional-cognitive and emotional reference as illustrated by Takakusaki (2013). The stimulus that generates gait (or the sensory signal in this illustration) activates cortical and sub-cortical structures as the information cascade propagates down towards the spinal cord for the automatic process.

1.1.2 Characterization of Human Gait

Gait is often described as a pattern of walking, consisting of different phases and events that occur in a cyclic pattern. For example, if a person started walking with their right foot, the cycle begins when their right-heel hits the ground, in the event called heel-strike, and the right leg is in the stance phase (the duration of which is termed stance time). The stance leg does not move during this time and acts as the pivot point for the body to move forward. During this right leg stance period, the left leg is in swing phase (the duration of which is termed swing time), where this leg is propelled forward, beyond the stance leg, to move the body's center of mass. As the left leg ends the swing phase, the left heel strikes the ground and the left leg is now in stance phase. Following this, the right leg transitions from stance phase into swing via the toe-off event where the right foot is propelled forward, initiating the swing phase for the right leg. This cyclic pattern of movement is what we call the gait cycle (see figure 2).

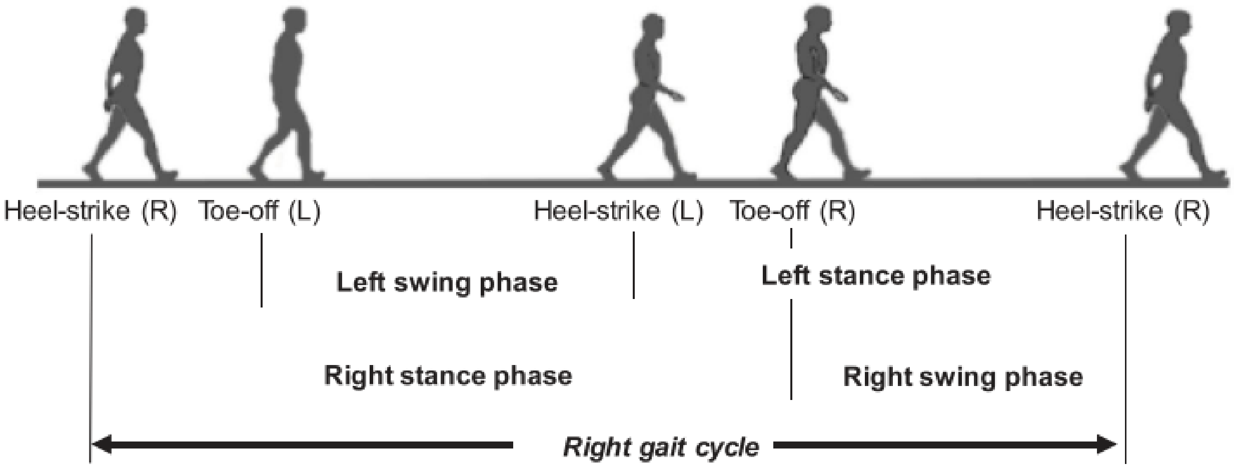

Figure 2: Shows the phases and events of a typical gait cycle, depicted is the right gait cycle (Deligianni et al., 2019).

Gait patterns are quantified numerically via specific measurements that take place during this cycle. These measurements can broadly fit into four categories: spatial, temporal, kinematic and kinetic measurements of gait (Chambers & Sutherland, 2002; Hollman et al., 2011). Commonly measured spatial parameters consist of measurements such as step length and step width, while temporal parameters consist of cadence (steps/unit time) and step time(Hollman et al., 2011). Spatiotemporal measurements such as gait speed (measured in m/s, cm/s) and stride speed (steps/unit time) are also commonly recorded (Hollman et al., 2011). Kinematic parameters involve measuring range of motion of different joints and segments of the body, commonly reported as flexion angles, elevation angles or movement distances of specific joints/segments as a person walks (i.e. elbow flexion, neck flexion, thigh elevation, arm swing etc.) (Chambers & Sutherland, 2002; Deligianni et al., 2019). Kinetic parameters involve measuring forces that are present during walking. Common parameters in this category involve center of pressure, ground reaction force (force of the landing heel strike on the ground), and center of mass (Chambers & Sutherland, 2002; Deligianni et al., 2019; Kim et al., 2019). Many studies use a combination of these parameters when assessing gait and compare differences in these parameters across individuals or groups of people.

Gait models, like ones created by Lord et al. (2013) are also used in clinical gait analysis studies. These models provide a selection of gait characteristics that are relevant when comparing healthy populations to other healthy or clinical populations. The 5-factor model created by Lord et al. (2013) was developed and validated based on the gait patterns of 189 older healthy adults and determined that the five independent factors of pace, rhythm, variability, asymmetry and postural control (and their associated discrete gait features, shown in figure 3) explained a majority of gait variance observed in the participants(Lord et al., 2013; Wilson et al., 2019). Alongside commonly measured gait parameters, this gait model also includes the measurements of gait variability which is shown to be clinically relevant in various psychiatric and neurological conditions. (Dragašević-Mišković et al., 2021). A recent study investigating the

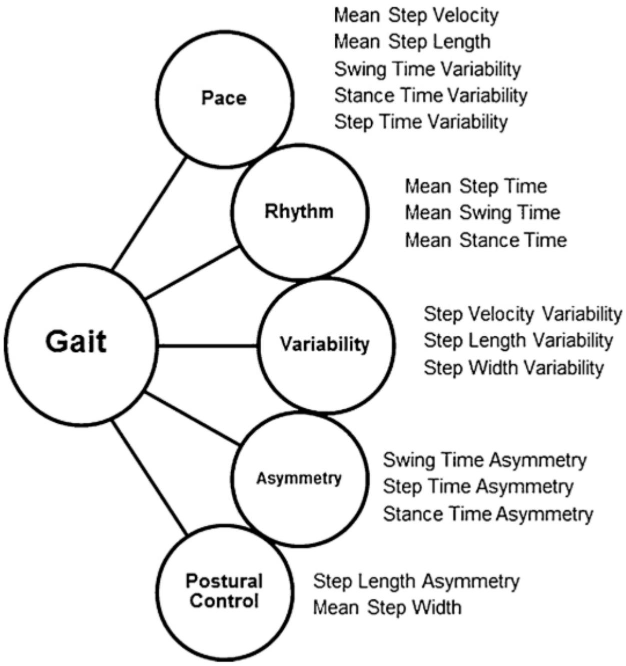

Figure 3: The 5-factor model of gait developed as depicted by Wilson et al. (2019). Each factor contains the specific parameters of gait involved.

impact of depression on gait variability in Parkinson's Disease (PD) patients showed that measures of variability (namely swing time variability) was significantly different in PD patients who suffered from depression compared to non-depressed PD patients (Dragašević-Mišković et al., 2021). Overall, gait models are an excellent tool that can help researchers standardize the way in which gait patterns are examined in an effort to understand how various factors impact gait patterns. These factors can include pathological states, individual traits, and even emotional states.

1.1.3 Gait and Emotion

Emotions, as described by Kandel (2013), are "automatic, largely unconscious behavioral and cognitive responses triggered when the brain detects a positively or negatively charged significant stimulus." (p. 1079). Although "largely unconscious" may be subject to argument as emotions can be voluntary and conscious decisions, the main purpose of emotions as Kandel (2013) alludes to is a way for the body to act and respond to stimuli. From the previous example, the stimulus that generates gait (thirst and a source of water at a nearby table) creates a cascade of activity from cortical and sub-cortical brain networks that eventually reach the central pattern generators and generate gait. This stimulus also activates the limbic system and a separate cascade of information processing stemming from the limbic system that projects into the brainstem and eventually the spinal cord is formed, termed the "Emotional" reference (see figure 1) (Takakusaki, 2013). Structures within the limbic system, including the hypothalamus, amygdala and the cingulate cortex, are associated with emotions, behaviour and motivation (Deligianni et al., 2019). Mirroring the structures that are involved in the "Volitional-Cognitive" reference, these neural structures of the limbic system also have connections to the PFC, BG and thalamus (Deligianni et al., 2019; Takakusaki, 2013). The shared circuitry between the emotional system of the brain (Emotional reference) and the widespread network involved for gait control (Volitional-Cognitive reference), presents a common neural basis for interactions between emotion and gait. A growing body of research has recently begun investigating the role of emotion on gait and how different emotional states might shape human gait patterns.

1.1.4 Emotion Recognition from Gait

Montepare et al (1987), investigated human perception of gait and whether participants could reliably detect different emotions from observed gait patterns. 10 participants observed the movements of 5 walkers (non-actors who were instructed to walk after reading a certain scenario depicting the emotions of happiness, sadness, fear, anger, and pride) as they performed their emotive gait. Video (captured from the neck down to remove effects of facial expressions) was collected from each walker which was played back to the participants for emotion detection. The results showed that emotions of happiness showed longer stride length and gait speed compared to sadness which showed lower gait speed and reduced arm swing. Anger also was seen to have a faster and a “heavy-footed” gait compared to the other emotions. The gait parameters themselves were not statistically compared, rather these results were the self-reported outcomes made by the observers. When identifying emotions from gait, the observers were more proficient in identifying sadness and anger compared to pride. One notable observation made by the authors suggested that the expression of emotion in gait varies by person and that some of the walkers were much better and more expressive at performing emotive gaits than others, potentially skewing the results that they observed. Although the sample size of walkers and observers were particularly small (n= 5 walkers, n = 10 observers), this work still was one of the earliest studies that established a link between observable gait patterns and emotion. The results highlighted similarities of gait patterns affected by anger and happiness (faster gait speed, longer strides) compared to sadness and fear (slower gait speed, shorter strides) which further research has also confirmed.

1.1.5 Effect of Emotion on Gait in Actors

Recent studies have also directly examined the effect of emotion on gait using actors that were instructed to recall certain emotions using past experiences to evoke emotions whilst gait kinematics were recorded (using VICON or point-light markers) (Barliya et al., 2013; Halovic & Kroos, 2018; Roether et al., 2009). From the captured movement data, gait specific information was extracted and compared between the emotions of anger, fear, happy/happiness, sadness and a neutral state. For example, cadence (i.e., how many steps each participant took per a fixed unit of time) was commonly compared across the different emotions. Additional kinematic features such as joint angles (elbow flexion angles, knee flexion angles, thigh elevation angles etc.) were also measured and compared across different emotions, albeit less frequently in past studies. Overall, the actor-based studies found that actors increased their gait speed (Barliya et al., 2013; Halovic & Kroos, 2018; Roether et al., 2009, cadence (Halovic & Kroos, 2018, stride length (length between the steps of the same foot) (Halovic & Kroos, 2018), and also showed increased joint angles (flexion angles) (Halovic & Kroos, 2018; Roether et al., 2009) whilst recalling emotions such as anger and happy/happiness. Phase timing (i.e., the duration of stance phase and swing phases) was measured by Barliya et al. (2013) and showed that happy and angry gait contained longer swing times (and thus a reduced stance time) which contributed to a faster gait cycle. Conversely, emotions of sadness or fear showed the opposite effects in actors. Gait patterns were characterized by slower gait speed (Barliya et al., 2013; Halovic & Kroos, 2018; Roether et al., 2009), shorter stride lengths (Halovic & Kroos, 2018), reduced joint angles (Roether et al., 2009), and longer stance times accompanied by shorter swing times (Barliya et al. 2013) whilst recalling sadness and fear. The overall goal of each of these studies was to distill down specific gait parameters that were influenced by different emotions, relying on actors to reliably produce representative emotional gaits. Both Barliya et al. (2013) and Roether et al. (2009) used a mixture of actor and non-actor groups in their study, whilst Halovic & Kroos (2018) used only professional actors. Barliya et al. (2013) contained a mixture of professional actors (n= 8) and non-actors (n=13) while Roether et al. (2009) contained a mixture of non-professional actors (6mo-2 years non-professional acting experience; n = 13) and non-actor/novices (no acting experience; n=12). Both studies reported that there was no significant difference in movements observed between the two groups, and Roether et al. (2009) even combined the two groups together for analysis when examining the overall differences in gait patterns as emotional states changed.

1.1.6 Effect of Emotion on Gait in non-Actors

Kim et al. (2019) further investigated this link using only non-actors (n= 12). In addition to collecting and analyzing the commonly recorded spatiotemporal parameters of gait (step count per minute and gait speed per minute) this study also looked at kinetic measures, recording the center of pressure distribution and peak plantar pressure of the emotions of calm, happy, sadness and a neutral control. These parameters were chosen in order to find meaningful markers of emotion in gait patterns. Unlike the previous studies, the researchers opted to use virtual reality (VR) and immersive video to elicit different emotions rather than using recall or reading a passage due to previous research showing greater effectiveness of a VR paradigm on eliciting emotions (Lorenzetti et al., 2018). Selecting specific emotional videos (such as being in a party for happy or watching turtles move around in a beach for calmness) they were able to effectively elicit the targeted emotion in their participants. Similar results are reported here as ones found by the studies discussed above where emotions of happy show greater step count and gait speed compared to the calm or neutral emotion while sadness shows the slowest gait speed. When looking at center of pressure, there is more pressure on the medial forefoot area during emotions of happy/happiness due to the increased gait speed. This localization of pressure moves towards the hind foot during the calm emotion and further back towards the heel in emotions of sadness. These results also establish that gait differences can be observed in a non-actor population where emotion elicitation occurs using external media and videos rather than an internal recall method.

1.1.7 Clinical Gait Patterns related to Emotional States

Lemke et al. (2000) approached this topic from a clinical perspective and compared gait patterns (measured by high-speed video camera) of patients with major depression (aged 25-60) and age matched healthy controls. Depressed patients when compared to healthy controls showed similar changes in gait parameters as one would see when comparing sad gait compared to happy gait-- as in there were reductions in gait speed, and reduced stride length. Clinically relevant gait parameters were also measured in this study that were mostly omitted from the previously discussed research. Namely, parameters related to phase timing (swing phase and stance phase time) and double limb support duration (duration of both feet on the ground). While the results showed no difference between depressed and healthy controls for the phase timings, double limb support duration was significantly higher in the depression population compared to healthy controls. Other clinical studies have shown that Parkinson’s disease (PD) patients who display severe gait abnormalities such as freezing of gait, which is an unintentional and abrupt cessation of walking, also have impairments in recognizing emotions from facial expressions, and significantly greater freezing severity when experiencing high levels of anxiety (Economou et al., 2021; Ehgoetz Martens et al., 2014; Lagravinese et al., 2018). These studies further reinforce the link between emotional states and gait while establishing that emotion does not have to be actively manipulated for there to be observable differences in gait parameters that reflect different affective states (i.e., anxiety) which can provoke or exacerbate gait impairments. Table 1, summarizes the findings across several of the studies discussed above that investigated the link between emotion and gait patterns.

Table 1: Shows a summary of different studies, which emotions were studied, participant information and observed gait patterns.

Study	**Emotions Studied**	**Participants**	**Observed Gait Patterns**
(Halovic & Kroos, 2018)	Happiness, Sadness, Anger, Fear, Neutral	36 professional actors	Happiness: Longer stride length, increased arm movement Anger: Faster cadence Sadness and Fear: shorter stride lengths
(Roether et al., 2009)	Happiness, Sadness, Anger, Fear, Neutral	13 non-professional actors, 12 non-actors	Happiness: increased elbow and head angle Sadness: reduced head angle Fear: increased elbow and knee flexion Fear and Anger: increased elbow flexion
(Montepare et al., 1987)	Happiness, Sadness, Anger, Pride	10 non-actor observers, 5 walkers	Anger: increased ground reaction force of landing foot, increased stride length Sadness: lower arm swing
(Kim et al., 2019)	Sad, Joyful, Calm, Neutral	12 non actors	Happy: increased step count, gait speed and peak plantar pressure Sad and Calm: decreased step count, gait speed and peak plantar pressure
(Lemke et al., 2000)	Depression and Healthy controls	16 depression and healthy controls	Depression: lower gait velocity, reduced stride length, increased double limb support duration
(Barliya et al., 2013)	Anger, Fear, Happy, Sadness, Neutral	13 non-actors, 8 professional actors	Happy and Anger: increased gait speed, thigh elevation angle, step length, cadence Fear: reduced gait speed, increased thigh elevation angle Sadness: reduced gait speed

1.1.8 Overview of Current Gait and Emotion Research

From the results of the studies in Table 1, it is evident that emotion plays a role in human gait. Generally, emotions of joy/happy or anger result in a faster gait, increased stride length, increased arm swing, pressure localized to the forefoot, increased cadence, increased step count and these parameters will decrease in emotions of sadness and fear (Barliya et al., 2013; Halovic & Kroos, 2018; Lemke et al., 2000; Roether et al., 2009). However, these studies have only looked at the common parameters of gait and there are still many aspects of gait that are unexplored. Namely, gait variability, outlined by the 5-factor model, has been largely neglected, despite recent research suggesting that these parameters may be clinically relevant (Dragašević-Mišković et al., 2021; Lord et al., 2013). Whilst Lemke et al. (2000) and Barliya et al. (2013) have examined clinically relevant measures of gait (such as double support time and single support time), there remains gaps in the understanding of how emotion changes parameters such as step length variability, swing time variability etc. To date, there have been no studies that looked at emotion and gait through the gait model proposed by Lord et al. (2013) or similar models (Hollman et al., 2011; Verghese et al., 2007) highlighting the lack in the consistency of reporting the effect of emotion on gait. As shown by Table 1, emotion has an established effect on human gait and neglecting the role of emotions when conducting clinical gait analysis may confound conclusions drawn during clinical assessment.

It is also important to note that most of these studies used professional actors as a way to measure emotional gait (Barliya et al., 2013; Halovic & Kroos, 2018; Roether et al., 2009). Although Barilya et al. (2013) showed that there were no significant differences in movements performed by the actor and non-actor group when looking at general gait parameters (i.e. gait speed), upon closer look at the two groups, both the limited sample size (n= 21) and the discrepancy between sample sizes of the two groups (13 non-actors, 8 professional actors) are limitations that could have affected the results of the study. In fact, Roether et al. (2009) argues against using professional actors due to skilled actors producing highly trained, stereotyped and overlearned ways of expressions that may confound the kinematic data collected. This led them to use non-professional actors and naïve (no experience) actors as the two groups for their study and found that no significant difference was present in the two groups. Furthermore, Halovic & Kroos (2018) (n = 36, all professional actors) mentioned that some actors displayed some emotions better than others and these differences were not uniform across emotions, potentially impacting the kinematic data collected. It was also highlighted that using recall as a method of emotion elicitation may have had varying emotional impact on the person which might be reflected on their gait pattern (some actors may over-exaggerate happiness but under-exaggerate fear or sadness as the intensity of emotion elicited was not examined) and could have impacted the results (Halovic & Kroos, 2018). Although statistically there were no differences seen in kinematic data between an actor group and a non-actor group, there is justification for future gait-based research to use a non-actor-based population as it avoids the issues with over performing emotive walking.

It should also be noted that previous research investigating the effect of emotion on gait has focused solely only a discrete model of emotions as the primary way to distinguish between two emotions. The discrete model regards emotions as mutually exclusive affective states (i.e., when an actor performs an angry gait, they are only feeling anger and no other emotion). However, when performing emotion or affect related studies, participants rarely feel one specific emotion without feeling other similar related emotions (Posner et al., 2005; Watson & Clark, 1992). Therefore, probing the relationship between emotion and gait from a perspective of a different emotional model may provide novel insights into how different gait parameters change when experiencing different emotional states.

1.2 Emotional Models

Two different models of emotion, a discrete and a dimensional model can be contrasted when studying emotions (Deligianni et al., 2019; Marín-Morales et al., 2020). The discrete model of emotion follows the theories of basic emotions and proposes that there exists some finite number of fundamental emotions of happy, disgust, fear, anger, sadness and surprise (Ekman, 1992; Tomkins, 1962, 1963). Actual number of these fundamental emotions are debated frequently but most researchers agree on the range of 5-10 (Izard, 1977, 1992). These fundamental and mutually distinct emotions combine together in any number of quantities to form higher order and more complex emotions (Ekman, 1992; Marín-Morales et al., 2020).

The dimensional model represents emotions on a scale, (usually a two- or three-dimensional Cartesian scale) where every emotion is plotted as an (XY) or an (XYZ) point. The axes represent some fundamental property that is shared by all emotions (Deligianni et al., 2019; Marín-Morales et al., 2020). One example of the dimensional model is the circumplex model of affect (CMA), where different emotions are depicted varying on the two-dimensional scales or axes of valence (pleasure) and arousal (Russell, 1980). Three dimensional models also exist such as the Pleasure, Arousal and Dominance (PAD) model whereby every emotion has three dimensions and is depicted using positive or negative vales of pleasure, arousal or dominance (Mehrabian & Russell, 1977). Pleasure/valence is reported as the positive or negative aspect of the emotion felt, arousal is reported as how much attention or awareness or intensity is felt and dominance is reported as how much or how little control or influence the participant has over their situation (Marín-Morales et al., 2020; Mehrabian & Russell, 1977).

Dimensional models are more advantageous over discrete models due to poor resolution of the discrete models when characterizing complex and emotionally confusing stimuli (Eerola & Vuoskoski, 2011). When performing emotion or affect related studies, participants rarely feel one specific positive emotion without feeling other similar related emotions (Posner et al., 2005; Watson & Clark, 1992). Thus, discriminating between different emotions becomes difficult using just a discrete model. Dimensional models try to combat this issue by depicting different emotions on a continuum and assigning self-reported numerical values to each different emotion based on valence (pleasure), arousal, dominance, energy, tension, withdrawal and approach (Lang et al., 1998; Mehrabian & Russell, 1977; Thayer, 1989). For example, the circumplex

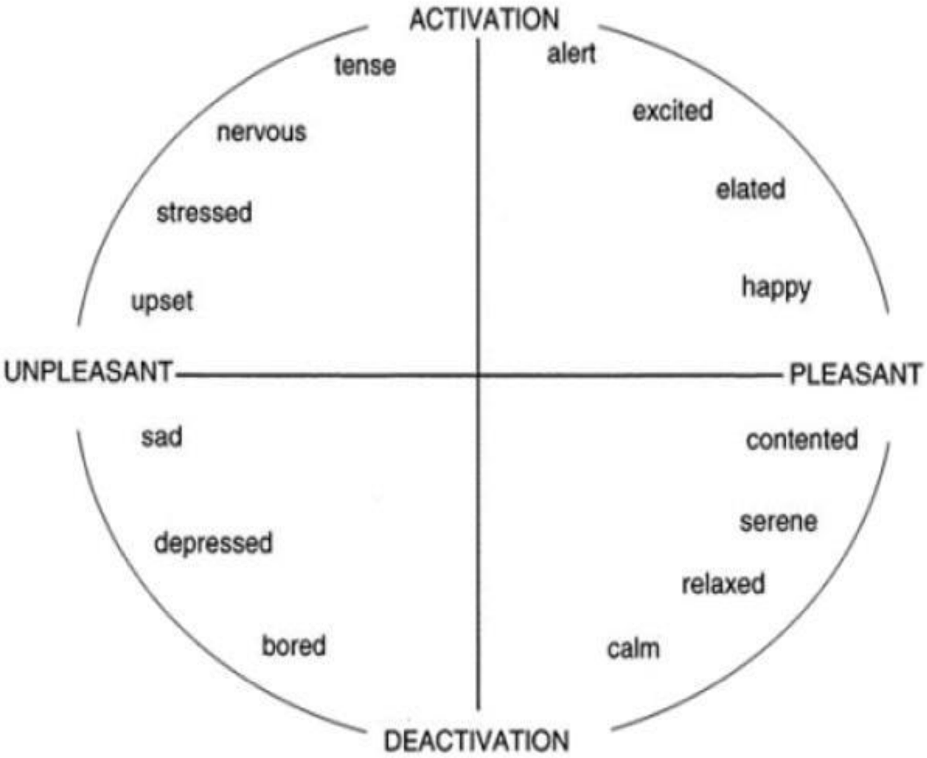

Figure 4: Shows the dimensional model: The circumplex model of affect. A two-dimensional model where horizontal axes represents positive and negative values of valence or pleasure and the vertical axes representing positive or negative values of arousal (Posner et al., 2005).

model depicts differences in sadness and depressed using different numerical values of pleasure and arousal (figure 4). While both are in the unpleasant and deactivation quadrant, depression, is characterized by a lesser value of deactivation (arousal) compared to sadness.

Dimensional models are not limited to just using valence, arousal or dominance for their axes, Lovheim (2011) introduces a new three-dimensional model for emotions using monoamine neurotransmitters of serotonin (5HT), dopamine (DA), and adrenaline (NE) as the axes (figure 5). This monoamine system was used as the foundation for this model because of the role of the human monoamine systems in regulating emotions and behaviour. Many clinical studies show that psychotropic drugs (antidepressants and anti-psychotics) act by influencing the monoamine system (Ebstein et al., 2000; Stahl, 2008). While the structures that release these monoamines in the upper brainstem areas (ralph nuclei, ventral tegmental area and locus cerulus) do not control emotions perse, it is the result of these monoamines production pathways that act upon the limbic system, amygdala, and cortex that ultimately impact emotional states and behavioral control (Lövheim, 2012).

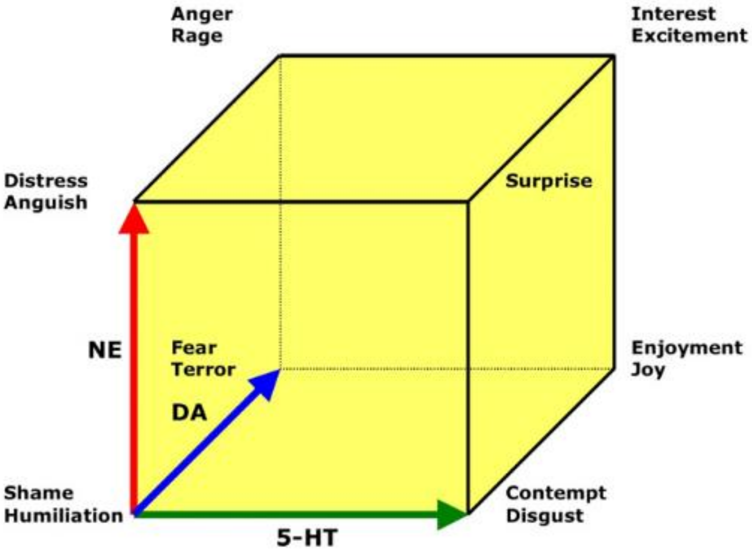

Figure 5: Shows Lovheim's Cube of emotions. Each vertex represents the most extreme emotion for that particular combination of neurotransmitter, derived from the earlier work of Tomkins. For example, Contempt/Disgust would have high amount of serotonin (5HT), but low amounts of the other two transmitters of adrenaline (NE) and dopamine (DA)(Lovheim, 2012).

The three axes of 5HT, NE, and DA are assumed to be coupled to different emotional concepts and characterize different attributes of an individual's cognitive-affective state. According to Lovheim, serotonin is coupled to self-confidence, inner strength and satisfaction as previous research shows those suffering from major depression and premenstrual dysphoric disorders appear to have low levels of serotonin and anti-depressants act by blocking serotonin transporters (Price et al., 2009). Dopamine is coupled to reward, reinforcement and motivation as shown by studies that implicate midbrain dopamine neurons that modulate the basal ganglia using signals related to reward and prediction (Haber & Knutson, 2010). Adrenaline is coupled to attention, vigilance and activity as it is involved in the fight or flight response (Flügge et al., 2004; Lövheim, 2012). In further defining the model, Lovheim (2011) used clinical studies for justification of which neurotransmitter (and axes) coincided with which particular pairs of emotions. The eight pairs of emotions were derived from earlier work by Silvan Tomkins who identified eight basic emotion pairs as innate affects which he considered "strictly biological portion of emotion". (Tomkins, 1962, 1963). The emotional pair of fear/terror and anger/rage are considered highly dopaminergic as clinical studies have shown that Parkinson's disease patients who have depleted dopamine levels have shown difficulty in recognizing facial expressions of anger and even show a dulled response to aversive stimuli, justifying its place in the high-dopaminergic category (Bowers et al., 2006; Lawrence et al., 2007). Anger has a been linked to serotonergic deficit in those with personality disorders, supporting its placement in the low-serotonergic area (Dolan et al., 2001; Lai et al., 2003). The inability to express interest (anhedonia) and major depression have also been linked with low serotonin (American Psychiatric Association., 1994). Thus, the emotions of interest and excitement were placed in the high serotonin axis. Other emotion pairs however lack this kind of justification via clinical studies or psychotropic drug-based studies. For example, fear/terror is shown as low-adrenergic, low-serotonergic and high-dopaminergic not due to any clinical studies but rather through the description of fear by Darwin, who described this fear as "…widely opened eyes, the relaxation of most muscles, and by the whole body cowering downwards or held motionless" (Darwin, 2009; Lövheim, 2012). Nonetheless, this model is the first to propose a dimensional view of emotion that is rooted in neurobiology. Although some parts of the model are based on assumptions (fear/terror) and there is a lack of research that directly examines the validity of this model, it still serves as an example of how different emotions can be studied using clinical populations and their role in changing concentrations of neurotransmitters rather than self-reported descriptions of emotion.

Taken together, using dimensional models of emotion we can investigate whether changes in gait from different emotional states are related to a low-dimensional components of emotion or alternatively, a discrete emotion itself. For example, as previous studies have shown, gait speed increases as in emotions of happy and anger compared to emotions of calm/neutral or sadness. Using the PAD dimensional model, it is evident that the emotions from sad to calm to anger also increase in levels of pleasure. Thus, using this approach we aim to determine whether pace (e.g. gait speed) maps onto pleasure axes in order to gain a more fulsome understanding of the influence of emotion on gait. Ultimately, this gives rise to the idea that perhaps it is not specific emotions of anger and happiness that increase gait speed nor the specific emotions of fear and sadness that causes decreases in these parameters but rather some underlying lower dimension of the arousal/pleasure/dominance axis.

1.3 Low Dimensional Relationship Between Emotion and Movement

In the set of emotions investigated by Kim et al. (2019) – happy, sadness, and calm/quiet – results showed that gait speed, was highest in happy, and lowest in sadness with calm/quiet being in between the two. Comparing these three emotions based on the PAD model, there is also a similar relationship between the three emotions (figure 6 for details). In both the pleasure and dominance axes, sadness was reported with the lowest values, joyful was reported with the highest value and calm/quiet was in between, mirroring the results seen in the gait speed. Similarly, as reported in table 1, the emotions of joy/happiness and anger share similar gait parameters, such as increased in gait speed, increased arm swing, and increased step count. Likewise, when these emotions are compared on the PAD model, it shows that they are both high in the arousal axes compared to the other emotions. Despite evidence of some relationship between gait patterns and the underlying low-dimensions of emotion, no study has investigated whether emotional changes to gait are dependent on this underlying level of arousal/ pleasure/ dominance rather than the explicit emotion experienced. Furthermore, one can extend this line of questioning to Lovheim's model. In accordance with Lovheim's model, emotions of anger and fear vary as a function of NE (adrenaline), whereas emotions of fear and joy/happiness vary on the 5HT (serotonin) axis yet both show increase in gait speed compared to fear which is low on both 5HT and NE. Although investigating these neurotransmitter concentrations in the brain to directly test this theory is beyond the scope of this thesis, from a theoretical standpoint we can consider the predictions that each model might make based on the suggested maximally different emotions.

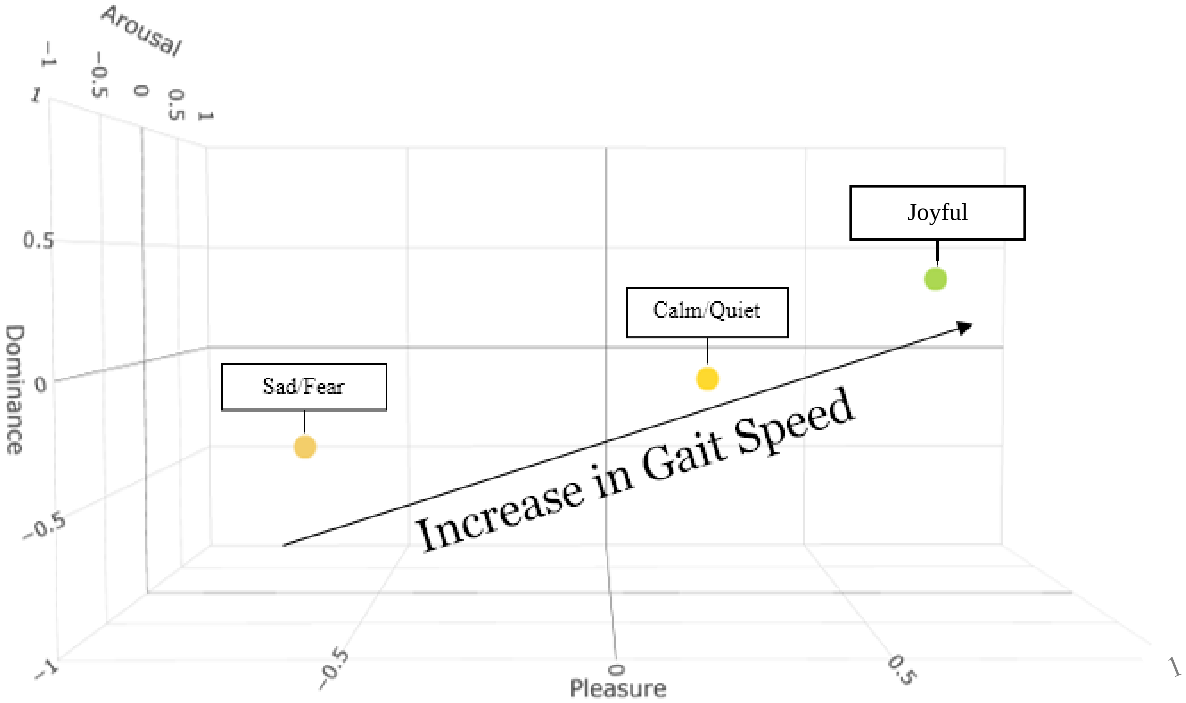

Figure 6 (Left): Shows the graph of the emotions of sadness, calm/quiet, and joyful with their respective pleasure (X), dominance (Y) and arousal (Z) values as reported by (Mehrabian & Russell, 1977). It is important to note that Mehrabain and Russell did not specifically state calmness as one of the emotions studied thus "quiet" was used as a substitute.

1.4 Gaps in Gait and Emotion Research

In sum, this thesis aims to fill several gaps within the literature of gait and emotion:

Gap 1: Few studies have been conducted that investigate emotional states on gait and much of the findings rely on limited sample of actors which could confound or exaggerate findings. Therefore, further research is needed to examine changes in gait that result from emotional state induction in a healthy young adult population.

Gap 2: Many previous studies have looked at repeating common gait parameters predominantly in the pace domain (e.g. gait speed, cadence, step length, stride length) but other domains of gait that are relevant to clinical gait analysis have been largely unexplored. Given that gait variability is one dimension of the 5-factor model created by Lord et al. (2013) that has largely been neglected in the literature to date (figure 3), further work is needed to better understand the influence of emotion on gait variability.

Gap 3: Finally, no research to date has examined changes in gait patterns using a dimensional model of emotion; coupling changes in gait parameters to specific dimensions of pleasure, arousal or dominance. Almost all previous studies have considered emotions as discrete affective states rather than a continuous variable that changes based on an underlying component (pleasure, arousal or dominance). To more broadly understand the impact emotion has on gait beyond discrete changes associated with discrete emotions, it is necessary to better understand the relationship between gait parameters and dimensions of emotion such as pleasure, arousal and dominance.

1.5 Objectives and Hypothesis

The main objective of this study is to address gaps 1 and 2 and measure the effect of emotional states on gait characteristics in healthy young adults with no acting experience using a broader set of new and previously examined gait parameters. This study used the gait model created by Lord et al. (2013) and investigate gait parameters across 4 domains of gait: pace, rhythm, variability, and postural control. These domains of gait contain not only previously examined gait parameters such as step velocity and step length, but they also contain new parameters such as swing time variability, step velocity variability, step time, swing time, stance times etc. These new parameters are important to this first objective as they contain clinically relevant parameters that are largely unexplored when it comes to emotion and gait research (Dragašević-Mišković et al., 2021; Lemke et al., 2000). Figure 7 shows a detailed list of the gait domains and the specific parameters that are contained within each domain.

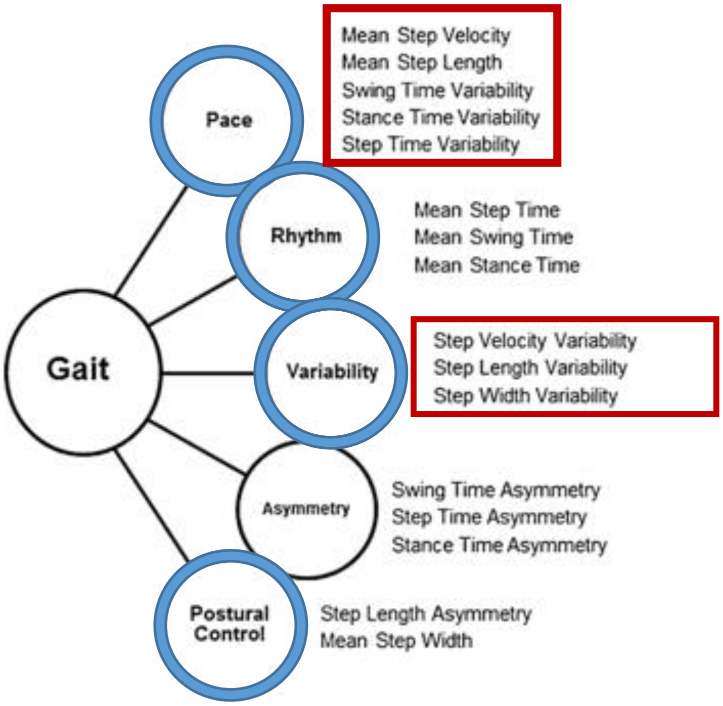

Figure 7: Shows the highlighted domains of gait, in blue, that is investigated in this study. The red boxes outline the parameters under the domains of pace and variability that are the main focus of the study.

While four different domains of gait are investigated, the focus of this study was largely on the domains of pace and variability. This was due to the lack of previous research in gait parameters that coincide with the domains of rhythm and postural control. Previous research in gait and emotion or gait and mood disorders (such as anxiety/depression) have mainly looked at the gait parameters under the domains of pace and variability. To achieve the goals of objective 1, the protocol involved to induction of emotions that have been studied in previous literature to ensure valid comparisons between results of this study and previous findings. This study aimed to elicit the emotions of happiness, sadness, anger, fear and excitement alongside a neutral emotion as a control. To evaluate the effect of emotion on gait behaviors, emotions were induced using VR and immersive video, whilst gait was quantified using a gait carpet. The various domains of gait we aim to examine and the listed hypotheses for the domains of focus are listed in Table 2.

Table 2: Shows the general gait domains that we aim to examine under different emotional states alongside general indicators of how they are expected change compared to a neutral state. Green arrows indicate a general increase in that parameter whilst red arrows indicate the opposite and blue rectangles indicate a possible change in either direction. Each emotion is also shown with its relative placement on the axes of pleasure, arousal and dominance, where a + (green) indicates that this emotion is positive in that axis and a – (red) indicates that it is negative on that axis (Mehrabian & Russell, 1977).

	PAD Model			**Gait Domains**	
Emotions	Pleasure	Arousal	Dominance	Pace	Variability
Excitement	+	+	+	⬆	▬
Happy	+	+	+	⬆	▬
Anger	-	+	+	⬆	▬
Fear	-	+	-	⬇	⬆
Sadness	-	-	-	⬇	⬆

Due to lack of previous literature on the domains of rhythm and postural control with emotions, Table 2, only shows hypotheses based on the main domains of rhythm and variability as this was the focus of the study. Based on the findings that investigated spatiotemporal parameters, it was hypothesized that emotions of happy, excitement and anger would result in increased gait speed and step length compared to the neutral control emotion (Barliya et al., 2013; Halovic & Kroos, 2018; Roether et al., 2009). Consequently, emotions like fear and sadness were expected to result in the opposite, showing decreased gait speed (Deligianni et al., 2019; Roether et al., 2009). Happy, excitement and anger conditions may also show increased steps (step count) during the walking trials while the opposite was hypothesized for emotions of sadness and fear as seen in studies examining spatial parameters (Kim et al., 2019; Montepare et al., 1987). Based on findings of Lemke et al. (2000) who studied differences in gait characteristics in depressed vs healthy controls, the emotions of sadness and fear was hypothesized to also show increased duration of stance time, decreased step time, and decreased gait speed compared to the emotions of happy, excited and even the control ‘neutral’ emotion. Based upon studies that looked at PD patients with depression, depression was shown to have an increase in gait variability which could imply that negative emotions (like sadness or fear) may increase gait variability, compared to other positive emotions and the neutral state. Due to similar responses in fear and sadness in gait characteristics, it was also hypothesized that fear would show an increase in gait variability. However, it was difficult to apply the same results and hypothesize similar changes in the other conditions of emotions in a healthy young adult population and thus the measures of variability are seen as parameters that could either increase or decrease depending on emotion.

The second objective of this study is aims to address gap 3 and examine the relationship between gait parameters and the dimensions of emotion. Using the PAD model, this study aimed to investigate whether movement parameters fluctuated based on the dimension of emotion that varies (e.g., pleasure, arousal or dominance). By examining emotions across both positive and negative dimensions of the three axes (positive and negative pleasure, arousal, and dominance), it was possible to evaluate whether the gait parameters can be explained by low dimensional changes in this emotional embedding space. It was hypothesized that a positive relationship would be seen between pleasure, arousal, dominance and the domain of pace. Generally, emotions that rate higher in the self-reported dimensions of arousal, pleasure, and dominance would result in increased values in the domains of pace, specifically, increased pleasure and arousal would be associated increased gait speed and increased step length (Table 2). Figure 6 shows how increases in pleasure coincides with an increase in gait speed observed, thus we extend those findings to the other related areas in the domain of pace. The domain of variability, rhythm, and postural control remain under studied and thus exploratory correlation analyses were performed to examine their relationship to pleasure, arousal and dominance.. Based on research showing a relationship between depression and increases in gait variability (Dragašević-Mišković et al., 2021), it was hypothesized that a negative relationship would be seen between pleasure, arousal, dominance and gait variability.

2.0 Methods

2.1 Subjects and Eligibility Criteria

Twenty-six (n = 26) healthy young adult participants from the University of Waterloo (19 F, 7M) were recruited for this study. G*Power3 (Version33.1, Universitat Dusseldorf, Dusseldorf, Germany) was used to determine sample size using the effect size reported by Halovic & Kroos (2018). Effect size from gait speed was used as the key dependent variable as it is a reoccurring parameter measured across many of the studies. Assuming an alpha error probability of 0.05, a power (1-β error probability) of 0.8, and the reported effect size of 0.64, a sample size of 18 was calculated (Halovic & Kroos, 2018). The sample included adult undergraduate and graduate students aged 18-35.

Exclusion criteria included any previous difficulty experienced with VR environments such as nausea, lightheadedness, severe fatigue and other illnesses reported that could impact normal gait. Recent history of physical injuries that significantly alters gait is also part of the exclusion criteria including injured limbs, concussion, and use of assistive walking devices. Participants were required to complete and sign informed consent prior to participation in the study. All participants were healthy and injury free for both lower and upper extremities in the most recent six months, and no lower or upper extremity surgery in the last two years. Only participants having a leg length difference lower than 1.5% of the height (corresponding to a maximum of 0.03m) were included in this study to avoid an effect of a leg length discrepancy in the dataset. Furthermore, participants with no medical history of neurological or detectable psychological issues were recruited, as their responses to the emotional stimuli may be different than that of a healthy adult. Any participants currently taking medication that might induce mood swings, or attenuate emotional responses were also excluded from the protocol. Participants were informed that some video samples that evoke emotions of fear, sadness or anger may be traumatic, and they were able to withdraw their consent at any time.

2.2 Common Methods for Emotion Elicitation

Emotional elicitation can be categorized using two main methods, active and passive elicitation (Marín-Morales et al., 2020). Active elicitation methods involve directly involving subjects in scenarios of social interaction directly with other people or direct behaviour manipulation of the subject (Marín-Morales et al., 2020). Passive methods, involve presenting some form of external stimuli, including pictures, videos, sounds, narrative passages from a story or a combination of these factors that the participant must interpret, which elicits the emotional response. The International Affective Picture System (IAPS) and the International Affective Digitalized Sound System (IADS) are among the most commonly used tools when eliciting emotions in participants; as they contain previously validated images and sounds that are shown to reliably elicit specific emotions in participants (Choi et al., 2017; Nardelli et al., 2015).

Recently, virtual reality (VR) has also shown to be a useful and effective tool to elicit emotion (Lorenzetti et al., 2018; Marín-Morales et al., 2019). This is due to the benefit of the immersive environments that VR can create which are both effective in eliciting emotions and are highly malleable (Higuera-Trujillo et al., 2017; Marín-Morales et al., 2019). This level of “immersive-ness” is unachievable by previously passive methods using just pictures, videos and sounds. The effect of “feeling the stimuli” or “being there” is simply not present in the older methods which enables participants to feel more lifelike emotion from stimuli (Marín-Morales et al., 2019). The added benefit of using VR is also its unique advantage of being able to tap into all three dimensions of emotion (Pleasure, Arousal and Dominance, assuming PAD model is used).

Previously, the dominance dimension was largely inaccessible using pictures, videos or sounds as the participant would always be (in some form) removed from the stimuli (Marín-Morales et al., 2020). For example, if a picture or video was shown of a person who was scared or terrified, the participant would not necessarily feel themselves be scared or terrified but would rather have to imagine what they would feel like if they were the person in the picture/video shown. Now with the immersive nature of VR, researchers can create scenarios where the person themselves is in the fearful situation and more actively playing a role in emotion elicitation. VR increases the ability to analyze of the emotions involving the dominance dimension (namely fear, terror etc.) and is an effective tool in eliciting more life-like emotions (Marín-Morales et al., 2020).

Different environments and stimuli can be used in a VR space to elicit various emotions. VR has the ability to use simple pictures (not much different from IAPS), use 360^{o} video (panoramic video), or a fully 3-D immersive environment to elicit emotions. Higuera-Trujillo et al. (2017) investigated and compared real physical environments to photos, 360^{o} panoramas, and VR recreation of the physical environment to determine whether the psychological and physiological responses would differ in each scenario. The psychological responses were measured via two questionnaires which measured responses on a 7-point Likert scale. One questionnaire queried the complexity, pleasantness, affection state of the environment while the other questionnaire queried their state after exposure to the environment in terms of pleasure, arousal and dominance. The physiological response was measured using electrodermal activity (EDA) and heart rate signals captured throughout the exposure of the different environments. The results showed that the 360^{o} panoramic medium (of being able to look around the picture but not being able to navigate) and VR environment showed responses that were more similar to the real-life environment than the photograph medium (seen in both psychological and physiological responses). This was explained due to the increased feeling of "being there" and immersive qualities of both these mediums (Clemente et al., 2014; Haans & Ijsselsteijn, 2012; Riva et al., 2007). Once again, these results reaffirm the idea that using VR and immersive video over photos and digital "screen videos" can result in a more life-like and accurate experiences.

To date, only one study has used immersive video/360^o video to reliably elicit different emotions in individuals and measure gait parameters. Kim et al. (2019) recruited 12 healthy adults who participated in an experimental setup where the emotions of calmness, sadness and happy were elicited using 360^o video. Their objective was to use VR and immersive video to elicit the three different emotions and then measure kinematic and kinetic parameters of gait and correlate them to specific emotions. After a viewing of the specific emotional media via VR headset, step-count per minute, gait speed per minute, plantar pressure distribution and peak plantar pressure were measured as the gait parameters (the results of this study is discussed above in table 1). This work established the efficacy of the methods in eliciting emotion using immersive video in a VR medium. However, only three emotional states were measured, and the videos used to elicit emotion were selected not based on some previously validated library, like IAPS, but rather through the discretion of the researchers. The current study employed a similar emotion elicitation paradigm but selected validated emotional stimuli as well as measured a wider range of emotions to evaluate the effects of emotion comprehensively on gait.

2.3 Selection of Emotional Stimuli

To create a similar library of validated 360^o videos like IAPS, Li et al. (2017) established a public database of immersive VR videos (360^o videos) that corresponded with participant self-reported values of arousal and valence. Over the course of 6 months, the researchers collected 73 videos varying in length of runtime from 30s-10mins. A total of 95 undergraduate students (39 male 56 female) between ages of 18-24 were recruited to view the videos and report their arousal and valence after each video viewing. Three blocks of videos were prepared for each participant with each block containing between 2-4 videos, each participant then would watch between 6-12 videos per session. Each selected video was watched by a minimum of 15 participants and mean arousal and valence rating was tabulated for every video watched. The objective here was to create an open database of validated videos that future studies could use as a resource when designing studies aimed at exploring emotion and emotion elicitation. The 73 different video clips were measured and catalogued in the database using self-assessment manikins (SAM) which is a commonly used self-reporting tool when measuring the dimensions of emotion (Li et al., 2017; Bradley & Lang, 1994). The SAM is a non-verbal pictorial assessment technique that directly assesses arousal, pleasure and dominance associated with a participant's emotional reaction to the stimulus or environment (figure 8). A 9-point rating scale is associated with each dimension of the three axes of PAD and participants are asked to report their feelings of valence, arousal and dominance from each picture according to their current emotional state (Bradley & Lang, 1994; Li et al., 2017). However, in Li et al. (2017) only arousal and valence were measured, and dominance was not investigated.

Therefore, to elicit emotional responses, the current study used the VR database that was created by Li et al. (2017) to extract specific videos that pertain to specific emotions. There is an added benefit of also being able to compare the reported values of valence and arousal from Li's study and compare them to future reported values of valence and arousal from future participants as well as add a third dimension of dominance, to fully flesh out all dimensions of emotions experienced using the SAM. Based on self-reported data by the participants, the authors also recommend that the videos used to elicit emotions should be limited in time (maximal 12 min in length) as too much time spent watching the videos may cause an increase in feelings of fatigue/boredom in participants.

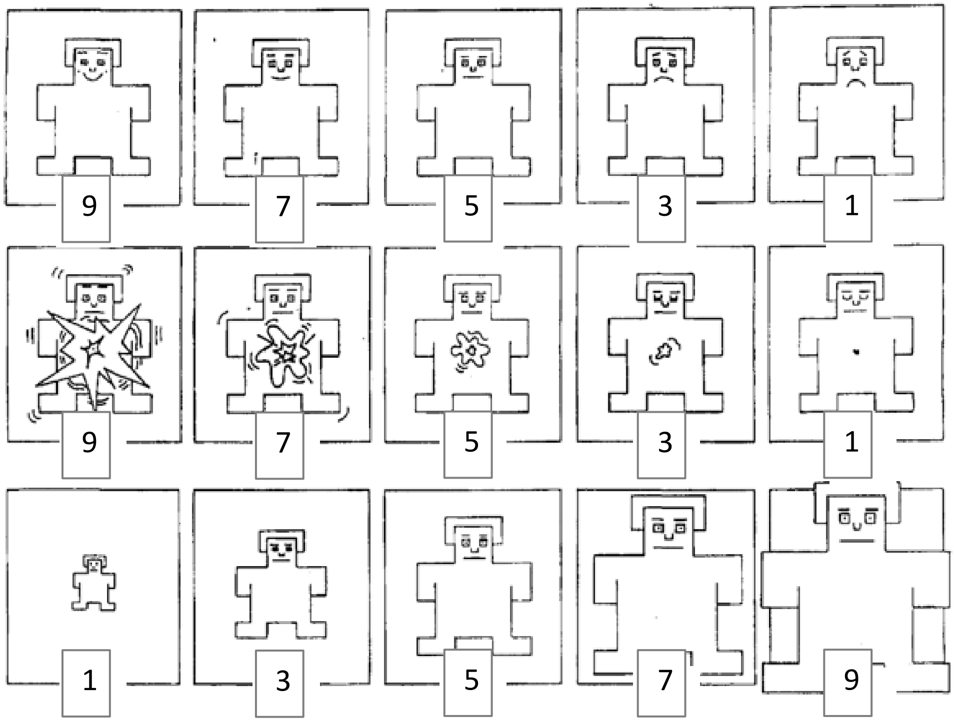

Figure 8: Shows the SAM with the top row being pleasure, followed by arousal and dominance. Participants can answer by reporting any figure or by reporting between figures (horizontally) which creates the 9-point scale of the SAM. For example, a SAM rating of 4 for Pleasure would be in-between the 3rd and 5th (value) in the top row (Bradley & Lang, 1994).

Table 3: Shows the list of specific proposed gait parameters intended to be examined. All measures of variability were determined using % coefficient of variation, calculated by the ratio of standard deviation divided by the sample mean.

Gait Domains	Gait Parameters
Pace	Mean Step Velocity
	Mean Step Length
	Step Time Variability
	Swing Time Variability
Rhythm	Mean Step Time
	Mean Swing Time
	Mean Stance Time
Variability	Step Velocity Variability
	Step Length Variability
	Step Width Variability
Postural Control	Mean Step Width

2.4 Lab Virtual Reality Environment

The HTC Vive was used as the head mounted display (HTC, USA). VR content was be generated using Unity (Unity Technologies, SF, CA, USA) and the immersive videos were embedded inside the VR environment using Unity. The HTC Vive is capable of presenting high fidelity video 1080 x 1200-pixel resolution and a viewing angle of 110^o.

2.5 Gait Parameters

Table 3 shows a list of all gait parameters the current study examined. Aside from the gait parameters associated with the pace domain, all other gait parameters have been scarcely researched when examining different emotions and gait. These gait parameters were chosen to add a more fulsome understanding of the domains of gait impacted by emotion which are relevant in clinical gait analysis (Lord et al., 2013).

2.6 Experimental Procedure

Upon arrival at the lab, participants completed a pre-test questionnaire in which participants self-reported their current emotional state. This questionnaire was a version of the modified Differential Emotions Scale (mDES) (Fredrickson et al., 2003; Philippot, 1993). The mDES used a 5-point Likert scale to evaluate the feelings experienced by the participant over the past two-week period. These questions evaluated both positive and negative feelings experienced by the participant by asking a series of 20 questions. Participants responded with a range of answers from (0) “not at all” to (4) “most of the time” for each positive or negative affect experienced over this period. For example: “I feel angry, irritated, annoyed” or “I feel amused, fun-loving, silly” are examples of negative and positive affect that the participant would report on the 0-4 scale. The total reported numbers were summed (0-40 for each negative and positive affect) and averaged out, resulting in a score between 0-4 for each of the positive and negative queries. Extreme emotional states were indicated by participants who consistently report high positive or high negative affect states. Participants who responded with extreme answers in the mDES in the positive and negative affect criterion were excluded from the study as their normal gait may be impacted by current extreme emotions. After initial demographic, eligibility and consent information was collected, initial calibration of the VR environment was made. Participants were given time to explore and navigate the virtual lab environment to familiarize them with the novel situation. If this study would be the first time a participant was in a VR environment, there might be confounding emotions of wonder, excitement and awe that may interfere with their normal gait. Thus, normalization of the participant to the environment was conducted here before any videos are watched and walking trials conducted. The walking trials involved walking from marker A (designated in the real lab environment with approximately 8m distance between the markers) to marker B on the floor and repeating 6 times. 6 repetitions of back-and-forth walking was approximately 50-60 steps of walking data collected on the gait carpet and motion capture (depending on stride length of the individual). These number of passes was chosen to meet two important objectives. First objective was to ensure that enough passes would occur to establish a steady gait pattern from the participants. Second objective was to ensure that enough steps would be recorded to get valid measurements of step time/length, swing times, double support times and gait variability (Perera et al., 2016). All measures of gait variability were calculated using %coefficient of variation (%CV). After calibration and normalization with the environment the video portion of the study was started.

Each video block was randomized to the participant but the two videos within each block were of the same emotional category. They were played inside the virtual environment and the participant was seated during viewing. Immediately after watching each video, participants self-reported their current emotional state using the self-assessment manikin (SAM) which has been used previously to measure pleasure, arousal and dominance values after an emotional stimulus has been administered (Bradley & Lang, 1994; Li et al., 2017). They were also be asked to answer, “How would you currently describe your emotion after watching the video?” This explicit response was used alongside the SAM to verify whether the targeted emotion was elicited in the participants. These SAM ratings helped compare gait parameters associated with specific values of pleasure, arousal and dominance to confirm whether the emotions intended to be evoked were in fact felt by the participant. After completion of the SAM questionnaire, participants removed the HMD and began their walk trials. All walking trials occurred in the real-world while the VR was used purely for emotion elicitation. Control walking trials (6 back and forth walking trials across the gait carpet) were conducted before viewing of the first block of emotional videos in order to establish the neutral/control gait trials. The walking trials continue after completion of the SAM for a total of 10 videos watched, and 11 walk trials

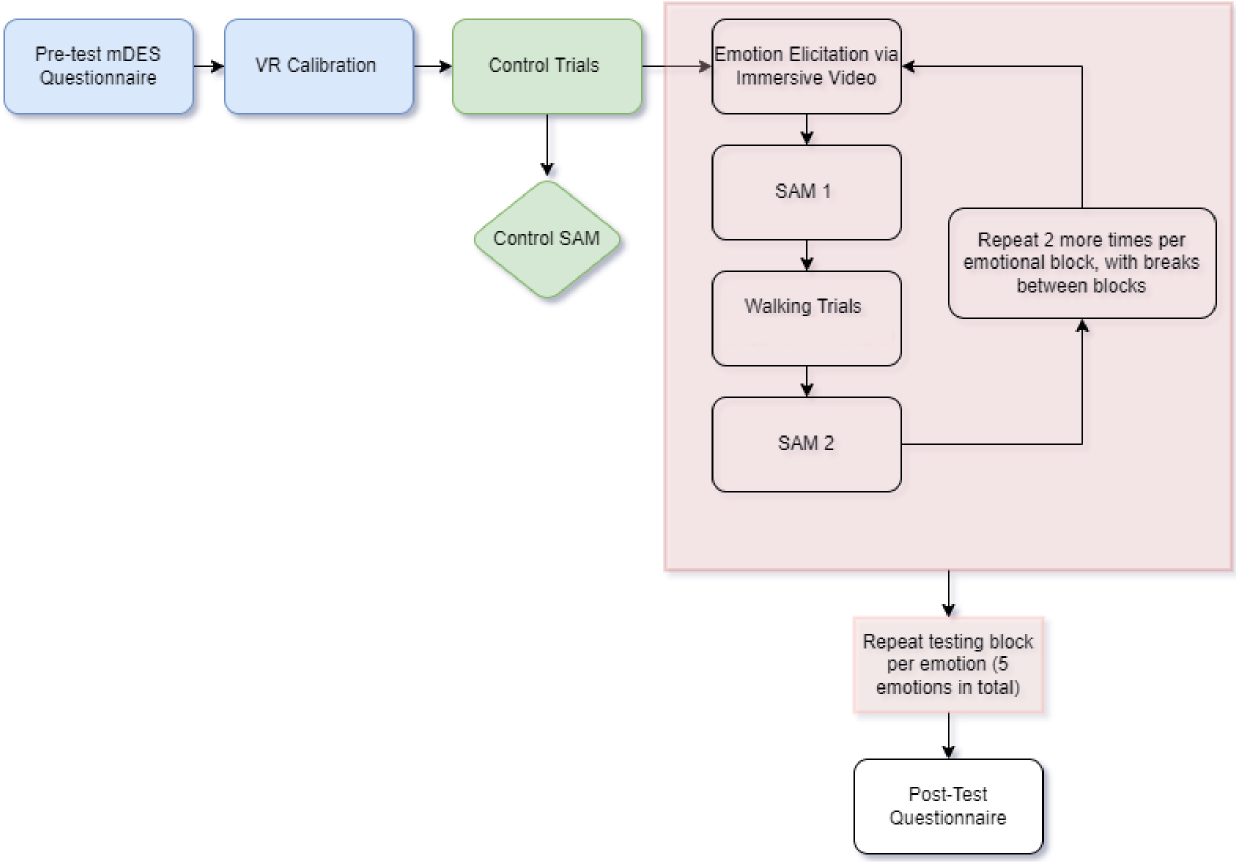

Figure 9: Shows the schematic of the experimental procedure.

performed (see figure 9 for schematic of procedure). The videos chosen were limited in their length (1 min to 6 mins depending on video length) to give frequent breaks to the participant as long durations spent in VR may induce feelings of sickness and fatigue (Li et al., 2017). The particular emotion that the video was intended to elicit was not disclosed to the participant in an effort to remove any outside bias during elicitation. Small breaks of 5 mins were offered between each block (but not between the video watching to walking portion) to reduce carryover effects of a certain emotional block onto the next one. After the study was completed, a post-test questionnaire (a simulator sickness questionnaire) was administered to evaluate any fatigue or illness experienced by the participant as it might impact gait results.

2.7 Data Collection

Spatiotemporal parameters of gait were measured using the Zeno^{TM} Walkway (ProtoKinetics, LLC, Havertown, USA) gait carpet. The PKMAS software (ProtoKinetics, LLC, Havertown, USA) was used to process and export the gait data for all emotional and neutral conditions. During data export, the first and last step made by the participant was excluded to control for the effects of acceleration and deceleration during gait initiation and termination. While multiple passes were collected, only the first pass (~20 steps) was used for analysis of the gait data.

2.8 Statistical Analysis

A one-way repeated measures ANOVA was conducted in R, comparing the above-mentioned spatiotemporal gait parameters across the five different emotional states to the control "neutral" emotion (6 conditions). If main effects of condition were present, a post-hoc comparison was made to determine which emotional conditions are different from one another in the gait parameter(s) observed. If there were no main effects of condition present, then a priori direct comparisons were made between each emotional condition and the neutral emotional condition. This also included measuring and testing for Sphericity and applying the Greenhouse-Geisser correction when appropriate. Post hoc comparisons with Durbin-Conover tests were also conducted when main effects are present and a significance level of $p<0.05$ was used for all analysis. Outliers were identified using the equation found in the rstatix package; values above Q3 + 1.5*IQR and values below Q1 – 1.5*IQR were considered outliers. Removal of outliers was only made if the data was seen to be a novel data point and was not definitive of the participant and their performance. This analysis addressed objective 1 which aimed to outline the differences in gait patterns observed between different emotions and a neutral state.

Correlational analysis using spearman's rank correlation coefficient was conducted to measure the relationship between gait parameters and the various self-reported dimensions of pleasure, arousal and dominance in order to address the second aim of the thesis. Gait parameters were correlated across the various scales of pleasure, arousal and dominance determine the relationship between emotional dimension and gait changes, similar to the graphs shown in figure 6. This analysis addressed objective 2 and outlined how individual changes in PAD may coincide with changes in gait characteristics observed.

3.0 Results

3.1 Emotion Elicitation

Whilst all 26 participants watched almost every video and completed all walking trials, not all participants reported feeling the emotion that was intended or targeted. Either through participant dropout or participants not feeling comfortable in the VR environment, some collections did not result in all emotion conditions being measured. Additionally, there were also scenarios where a participant could be watching a video that was intended to elicit anger but after watching the VR video, they could self-report that the emotion they felt was "confusion" or some other emotion that was not explicitly "anger". This was also reflected on their SAMs with varying reports of pleasure, arousal and dominance. Given the added variance of these untargeted emotions which could not be matched by other participants, these participants were removed from the analysis. The dropout of participants from certain emotional conditions also made pairwise and repeated measures analysis a challenge. Thus, a subset of 14 out of the 26 participants (9 female, 5 male) that explicitly reported they felt *each* of the targeted emotions was used. It was imperative to select for participants that reported *every single* of the targeted emotions in order to perform within-subjects tests and further pairwise comparisons.

To analyze the effect of the different emotions on gait, it was important to first identify how effective the videos were in eliciting the correct emotions. Figure 10 shows the frequency of the self-reported PAD scores of across all emotional videos as reported by the participants. Raw values of each dimension were binned into "Low" for scores of 1-3, "Med" for scores of 4-6, and "High" for scores of 7-9 on the SAM for clarity of interpretation.

A main effect of emotion condition on raw pleasure scores was seen when pleasure scores were compared across emotion condition (χ^2_{Friedman} ($df=5$) = 64.86, p =$1.20e^{-12}$, W_{Kendall} =

0.93, see Appendix A1). Pairwise comparisons revealed that each emotion condition except for anger and fear were significantly different from one another in their pleasure ratings ($p < 0.05$ see table A2). As expected, across the pleasure dimension, the positive pleasure emotions of

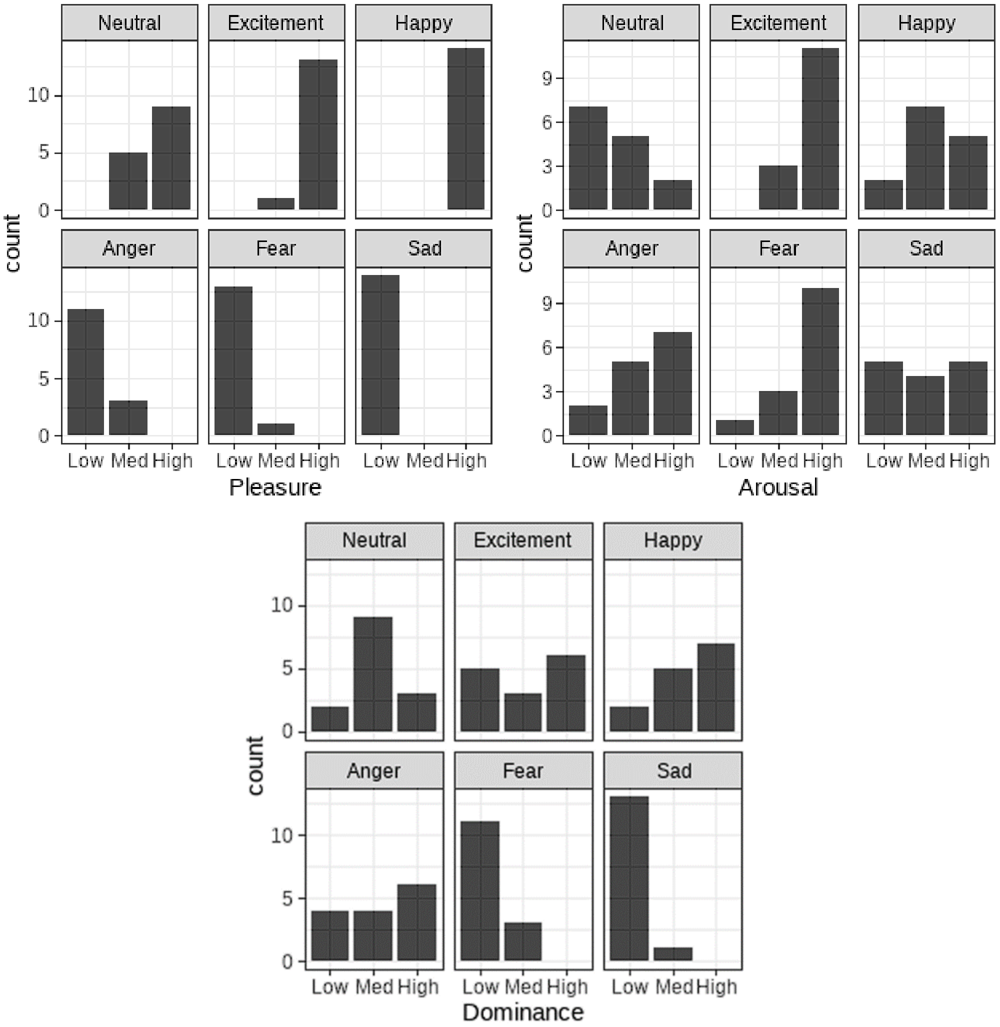

Figure 10: Displays the binned values of pleasure (top left), arousal (top right) and dominance (bottom) for each of the elicited emotions in the smaller subset of participants (n = 14).

excitement and happy showed greater scores on self-reported pleasure compared to the negative emotions such as anger, fear, and sadness.   A main effect of emotion condition was also seen when arousal score was compared across emotion conditions (χ^2_{Friedman} ($df=5$) = 33.73, $p = 2.70e^{-6}$, $W_{\text{Kendall}} = 0.48$, see A3). Post hoc comparisons showed that many of the emotions did not differ from each other in terms of raw arousal scores. Significant differences in arousal were mainly observed in the neutral condition which showed significantly lower arousal values compared to anger, excitement, fear, and happiness but not sadness. Significantly higher pleasure scores were seen in the condition of excitement when compared to happiness and sadness conditions ($p < 0.05$). Finally, fear was also found to have significantly higher arousal scores when compared across sadness ($p < 0.05$, see A4). Across the arousal dimension, excitement and fear showed the highest levels of arousal whilst the neutral condition showed the lowest levels of arousal. Interestingly, it seemed that many of the emotional conditions resulted in an increase in arousal as shown by the consistent increase in medium and high reports of arousal of all emotions compared to the neutral condition.

A main effect of emotion condition for dominance scores was also observed (χ^2_{Friedman} ($df=5$) = 36.38, $p = 7.97e^{-7}$, $W_{\text{Kendall}} = 0.52$, see A5). Dominance values were significantly lower in the fear and sadness conditions when compared across all other conditions ($p < 0.05$) whilst the fear and sadness conditions themselves did not show differences in dominance scores (see A6). No other comparisons showed a significant difference revealing that dominance was similar across the remaining conditions of neutral, happy, excited and anger. Across the dominance dimension, highest reports of dominance were observed in the anger, excitement and happy emotions (A5) and the lowest in the emotions of fear and sadness which was expected. In terms of eliciting the targeted emotions, figure 11 shows that the experimental procedure did have success in eliciting the target emotions in individuals and their SAM scores reflected similar values of pleasure, arousal and dominance across the different emotions as seen in previous literature (see figure 4 and table 2).

3.2 Gait Differences in Emotions

Across the four different domains of gait, 11 variables of interest were examined (see table 3) under the 6 different emotional conditions (5 emotional and 1 neutral baseline condition). Friedman's ANOVAs were conducted as parametric assumptions were violated in the dataset. Durbin-Conover pairwise comparisons with Bonferroni's corrections were also conducted upon reaching significant result with the Friedman's ANOVA ($p<0.05$). Significant differences in gait were only found in the domains of pace and rhythm while the domains of variability and postural control showed no significant results in the repeated measures ANOVA across the emotional conditions (see appendix for all ANOVA results). The next sections will only display significant results from the pace and rhythm domains.

3.2.1 Pace Domain

Figure 11, displays a main effect of emotion condition for step length ($\chi^2_{\text{Friedman}}(df=5) = 34.12$, $p = 2.25e^{-6}$, $W_{\text{Kendall}} = 0.49$) with a moderate effect size. Post hoc analysis showed that step length was reduced during the sadness condition compared to all other emotion conditions except fear ($p<0.05$, exact p values are reported the figures). Additionally, excitement had greater step length compared to fear ($p<0.05$). Median (IQR) values for the step lengths (cm) of the emotions are as follows in ascending order: Sadness – 59.14cm (6.21), Anger – 61.7cm (5.0), Fear- 62.0cm (6.23), Neutral – 63.0cm (6.18), Happy – 63.8cm (6.34), Excitement- 65.9cm (7.97).

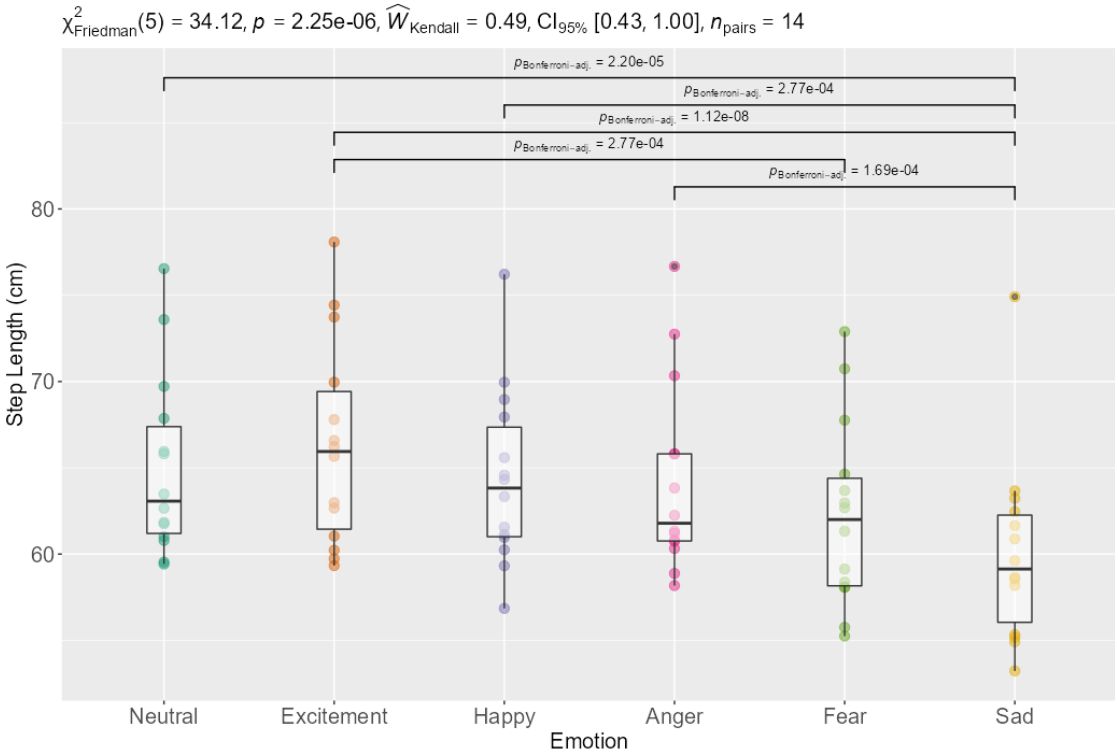

Figure 11: Displays the boxplot of each emotional condition and mean step length (cm) for each emotion alongside significant pairwise results, denoted by the brackets.

Figure 12 displays a main effect of emotional condition for gait velocity, (χ^2_{Friedman} (df = 5)=35.1, $p<1.44e^{-6}$, $W_{\text{Kendall}} = 0.50$) with moderate to almost large effect size. Post hoc analysis showed that gait velocity was reduced during the sadness condition compared to all other emotion conditions including fear, whilst gait velocity was also reduced during the fear condition compared to the excitement condition ($p<0.05$). Exact p-values can be seen in the figures. Median (IQR) values for gait velocity in cm/s are as follows in ascending order: Sadness – 110.5 (14.3), Anger – 117.5 (17.746), Fear – 119.7 (13.818), Neutral – 124.2 (21.4), Happy- 125.4 (24.3), Excitement – 129.5 (24.1).

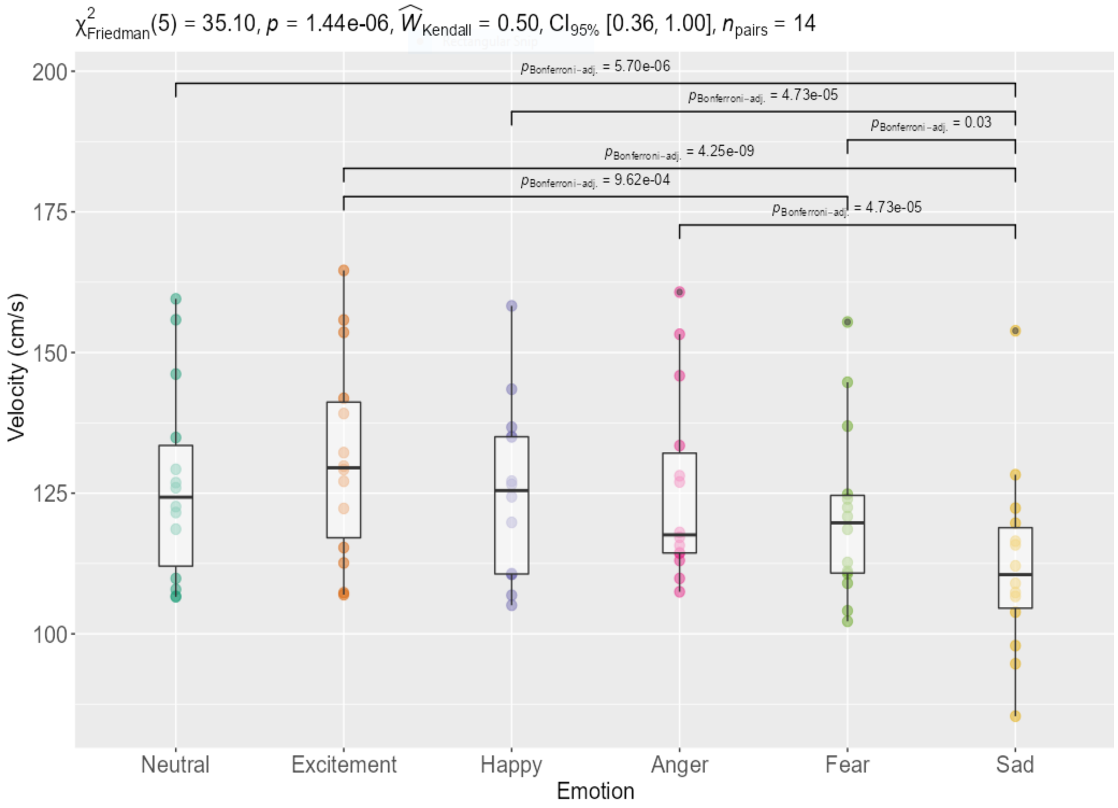

Figure 12: Displays the boxplot of each emotional condition and velocity (cm/s) for each emotion alongside significant pairwise results, denoted by the brackets.

3.2.2 Rhythm Domain

Across the rhythm domain, all three variables (i.e., swing time, step time, and stance time) showed significant results. Figure 13, displays a main effect of emotion condition for swing time (s) χ^2_{Friedman}(df = 5) =13.96, $p<0.05$, $W_{\text{Kendall}} = 0.20$ with a small effect size. Post hoc analysis showed that the sadness condition displayed longer swing times compared to both fear and excitement conditions ($p<0.05$). Although the spread of swing times is much more clustered in the fear condition compared to the other conditions, there was no statistical difference in swing time variability when comparing across any of the emotional conditions. Median (IQR) values for swing time in (s) are as follows in ascending order: Neutral – 0.392 (0.038), Happy –

0.394 (0.021), Fear- 0.408 (0.395). Excitement – 0.396 (0.02), Anger – 0.396 (0.02). Sadness – 0.401 (0.01).

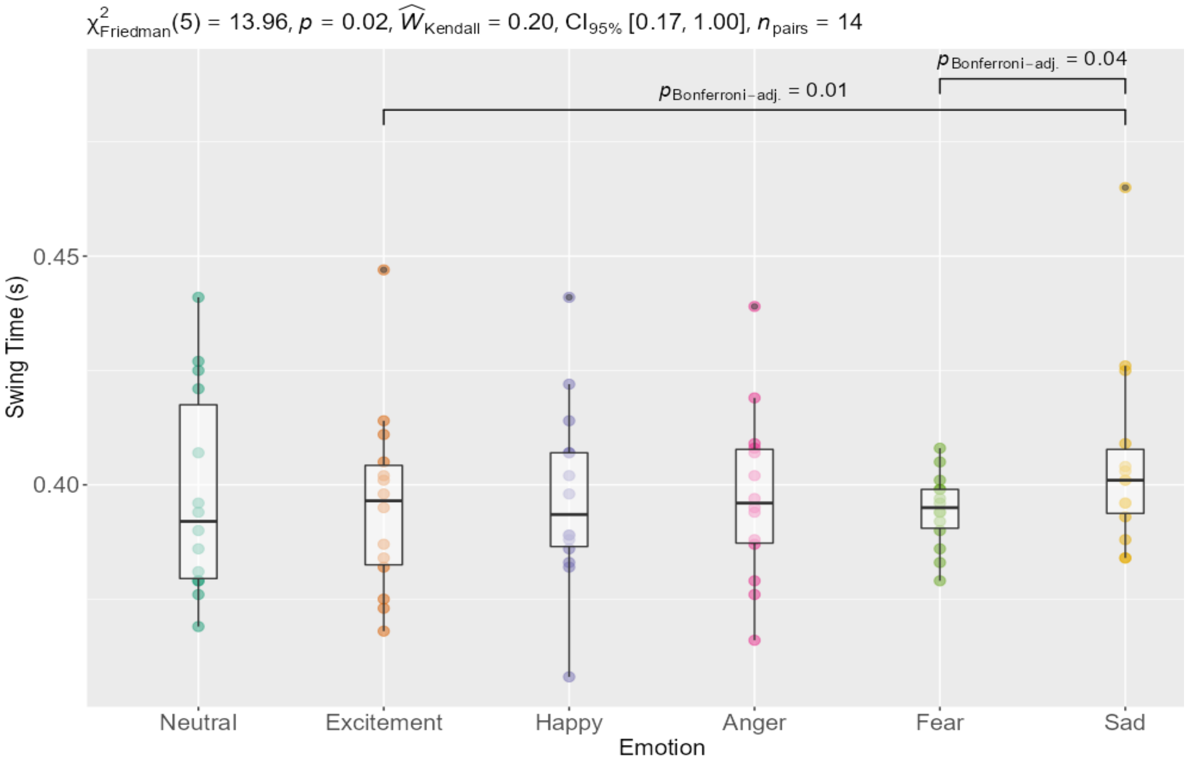

Figure 13: Displays the boxplot of each emotional condition and swing time (s) for each emotion alongside significant pairwise results, denoted by the brackets.

Step time, in figure 14, revealed similar results to the pace domain. A main effect of emotion condition was found for step time (s)χ^2_{Friedman}(df = 5) =24.97, p<0.02, W_{Kendall} = 0.35 with a moderate effect size. Post hoc analysis revealed that sadness resulted in greater step time compared to all other emotion conditions with the exception of fear (p<0.05). Notably, there were no other pairwise comparisons that revealed significant differences in swing time. Median (IQR) values for step time in (s) are as follows in ascending order: Excitement – 0.498 (0.043), Neutral – 0.512 (0.056), Happy – 0.513 (0.042), Fear – 0.516 (0.032), Anger – 0.522 (0.041), Sadness- 0.533 (0.043).

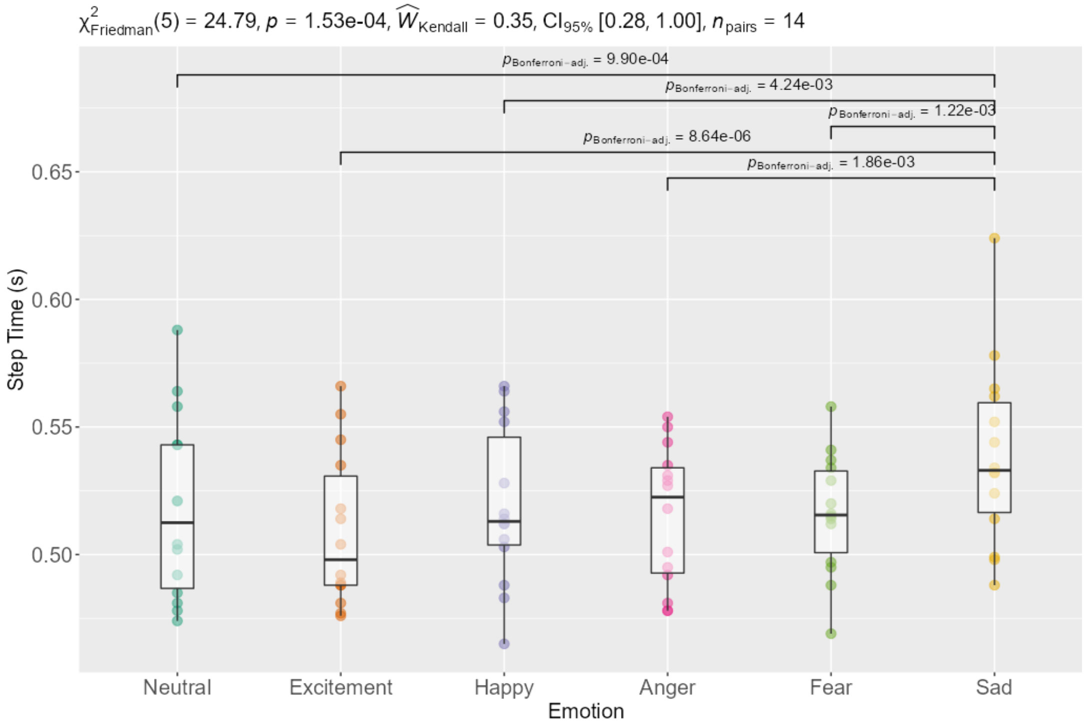

Figure 14: Shows the boxplot of each emotional condition and step time (s) for each emotion alongside significant pairwise results, denoted by the brackets.

Stance time is reported in figure 15, where a main effect of emotion condition was found for stance times (s) (χ^2 $_{\text{Friedman}}$ (df = 5) =28.74, $p<0.05$, W_{Kendall} = 0.41), with a moderate effect size. Post hoc analysis showed that sadness had higher stance times than all other emotional conditions ($p<0.05$) but no other pairwise comparison resulted in a significant outcome. Median (IQR) results for stance times in (s) are as follows in ascending order: Excitement – 0.619 (0.069), Neutral- 0.635 (0.061), Happy – 0.638 (0.077), Fear- 0.638 (0.056), Anger – 0.649 (0.055), Sadness – 0.673 (0.061).

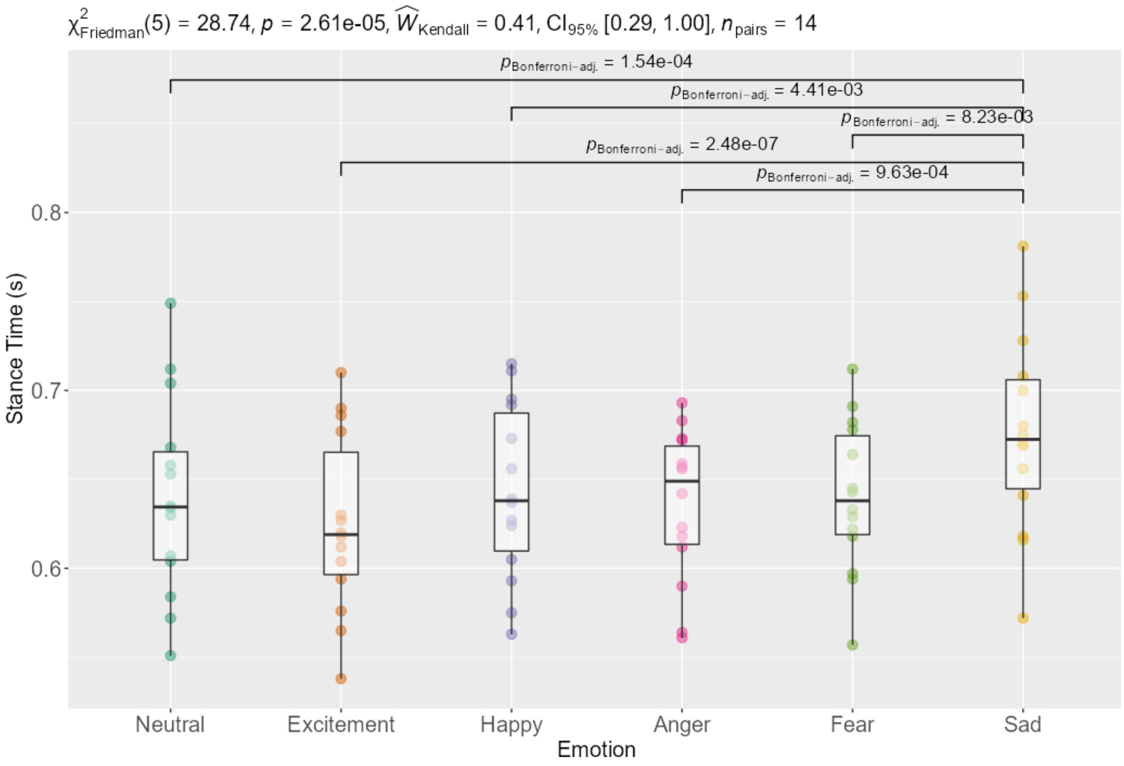

Figure 15: Shows the boxplot of each emotional condition and stance time (s) for each emotion alongside significant pairwise results, denoted by the brackets.

3.3 Gait and the PAD Model of Emotions

To relate changes in gait with the dimensions of pleasure, arousal, and dominance, spearman's rank correlation tests were performed with the three dimensions of PAD across the 11 gait variables. For these tests, the full dataset of all 26 participants was used as their discrete emotional reports were not required to correlate changes between PAD and gait variables. Results from significant correlations are presented below, non-significant correlation can be found in the appendix.

3.3.1 Pleasure and Gait

A significant weak positive relationship was found between pleasure and two gait variables, step length (ρ = 0.28, p = 0.0116) and gait velocity (velocity ρ = 0.25, p = $9.5*10^{-6}$). Figure 16 shows the scatterplots and correlations for step length and figure 17 shows the same plots for velocity alongside the reported spearman's rho. No other gait variables showed any significant association with pleasure.

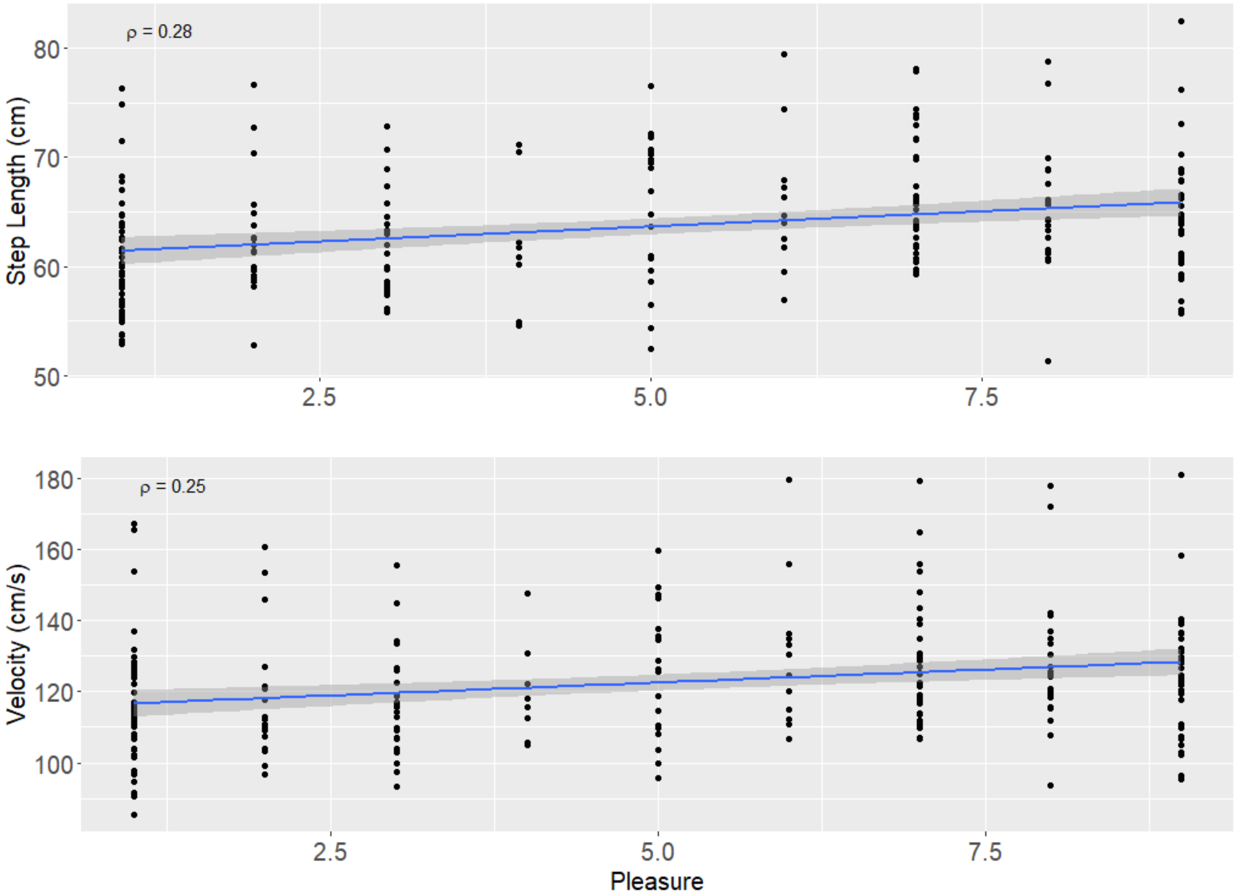

Figure 16(top): Shows the spearman's correlation test with pleasure and step length (cm). Blue line represents the line of best fit and shaded areas represents the 95%ile confidence level. Figure 17 (bottom): Shows the spearman's correlation test with pleasure and velocity (cm/s). Blue line represents the line of best fit and the 95%ile confidence level is represented by the shaded area.

3.3.2 Arousal and Gait

A significant weak negative relationship was found between arousal and stride velocity variability (ρ = -0.16, p = 0.01) as seen in figure 18. No other variable resulted in a significant spearman's rank correlation test.

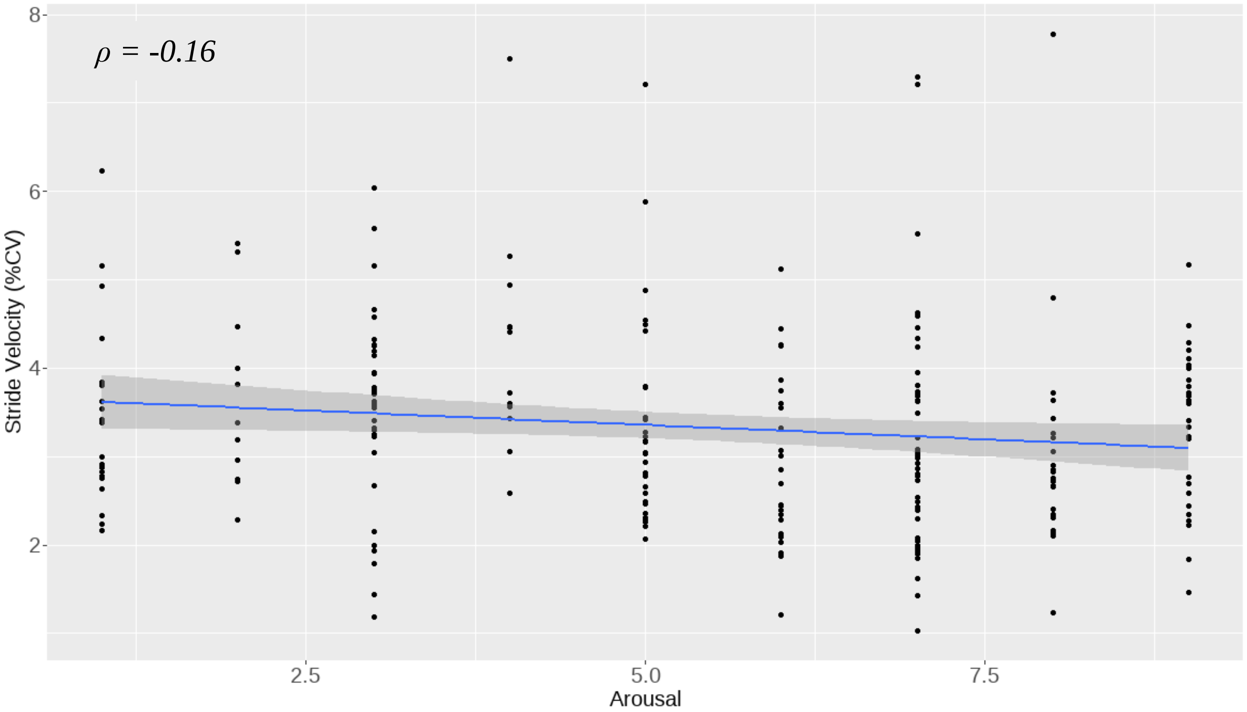

Figure 18: Shows the spearman's correlation test with arousal and stride velocity (%CV). Blue line represents the line of best fit and shaded areas represents the 95%ile confidence level.

3.3.3 Dominance and Gait

A significant positive relationship was found between dominance and the gait parameters of step length (ρ = 0.22, p = 0.0008) and gait velocity (ρ = 0.17, p = 0.009). A significant negative relationship was found between dominance and stride velocity variability (ρ = -0.14, p = 0.035) as seen in figures 19-21.

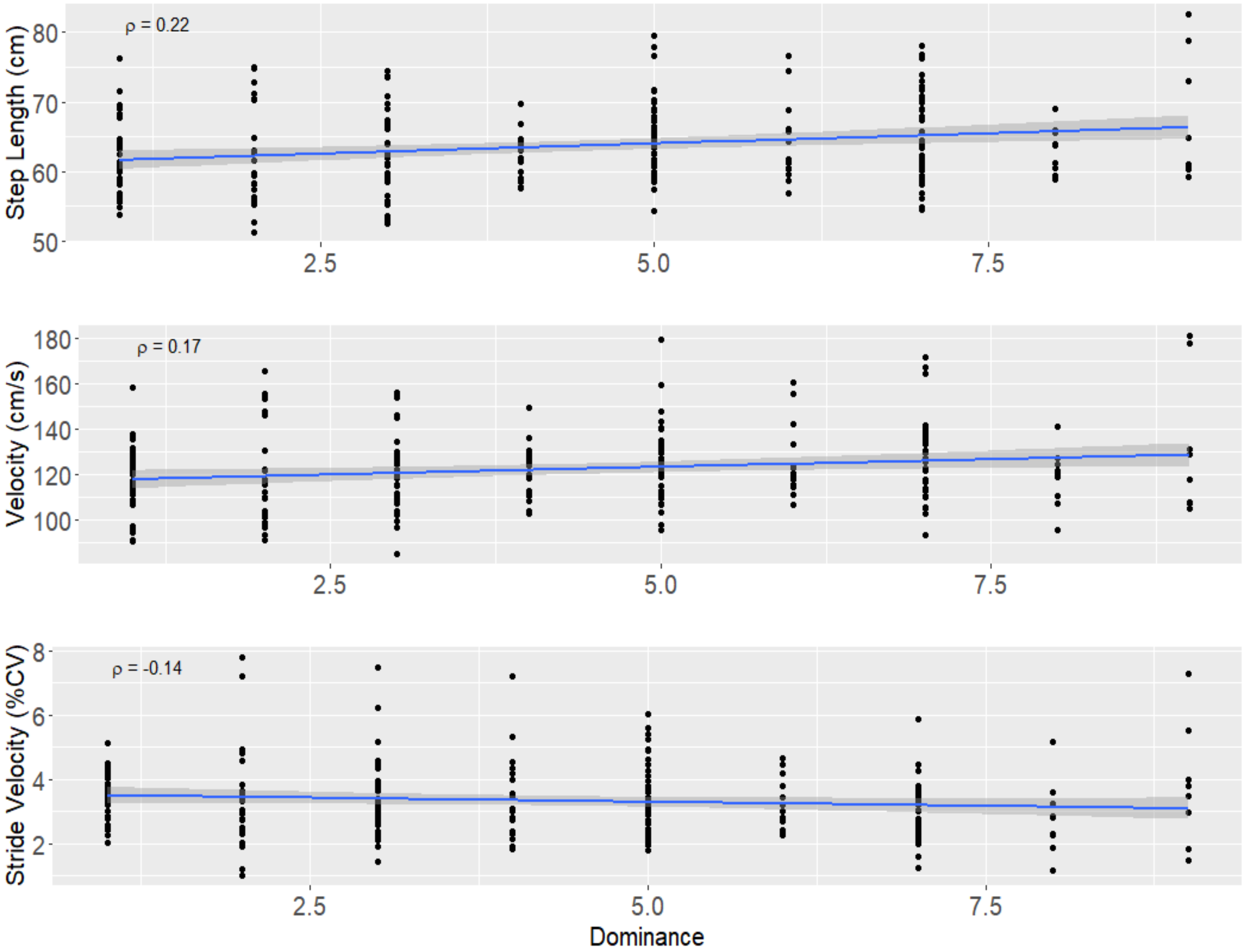

Figure 19(top): Shows the spearman's correlation test with dominance and step length (cm). Figure 20 (middle) Shows the spearman's correlation test with arousal and velocity (cm/s). Figure 21 (bottom) Shows the spearman's correlation test with dominance and stride velocity (%CV). Blue line represents the line of best fit and shaded areas represents the 95%ile confidence level; spearman's rho is reported on the top left of each figure.

4.0 Discussion

The primary objective of this study was to examine the influence of the discrete emotional states of happy, excitement, anger, fear, and sadness on gait parameters using the 5 factor model of gait in a healthy adult non-actor population. It was hypothesized that emotions of happy, excitement, and anger would result in increases in walking pace (i.e. step length and gait velocity) when compared to the neutral condition while the opposite was expected for emotions of sadness and fear. Results showed that indeed a reduction in step length and gait speed was present when comparing the sadness condition to other emotions and the neutral condition. However, no other emotion condition of happy, excited, fear, nor anger showed significant changes from the neutral condition in gait speed or step length. . It was also hypothesized that fear and sadness would result in increased variability of gait, however this hypothesis was not supported by the data as there were no changes in gait variability or postural control domains across any emotion condition. Results from the current study suggest that the majority of emotions elicited may not play a large role in influencing healthy adult gait– with the exception of sadness. Sadness, above all other emotion conditions showed the largest discrepancy in gait parameters across the dimensions of pace and rhythm, showing decrease in step length, gait velocity, and increases in swing time, step time and stance times when compared to the neutral condition and other emotional conditions.

The secondary objective of this study was to determine whether changes in gait could be associated with changes in the underlying dimensions of pleasure, arousal, and dominance instead of discrete changes in emotional states. It was hypothesized that pleasure, arousal, and dominance would be positively correlated with gait parameters in the pace domain whilst negatively correlated with gait parameters in the variability domains. Results showed that the pleasure dimension indeed had a weak positive correlation with step length and gait velocity (figure 16-17). A positive correlation was seen in the pace domain and pleasure, however no negative correlation was shown in the variability domain with pleasure. Conversely, the dimension of arousal was associated only with a weak negative correlation with stride velocity variability (figure 18). Whilst no correlation was seen within the pace domain, this result did support the hypothesis of arousal being negatively correlated with variability. The dominance dimension showed that it influenced both pace and variability domains. Results from this dimension showed that dominance was associated with weak positive correlations with step length and gait speed (pace domain) and was associated with weak negative correlation with stride velocity variability (variability domain), supporting both parts of the initial hypothesis for this dimension. Overall, these results showed that it is the dimensions of pleasure and dominance that were more closely associated with changes in gait behaviour than the arousal dimension. Most of the changes seen in gait were in the pace and variability domains, and these dimensions did not show any correlations with the domains of rhythm or postural control.

4.1 Emotions Impact Pace and Rhythm

Overall, the current findings from evaluating discrete emotions and respective gait changes support the evidence presented by existing literature. Similar to past work, the current study found increases in gait speed and step length in the pace domain during happy, anger and excitement emotions compared to fear and sadness emotions which reflect similar results reported by previous literature (Barliya et al., 2013; Halovic & Kroos, 2018; Montepare et al., 1987; Roether et al., 2009).

Barliya et al. (2013) showed that, the sadness condition resulted in the slowest gait speed and that fear, happy, and anger conditions showed faster gait compared to sadness (figure 22) which all are supported by the results of this study. Barliya et al. (2013) also reported that there were no differences in gait speed between the emotion conditions of neutral and happy which once again agree with the findings of this current study. However, Barliya et al. (2013) reported anger to be the emotion condition with the fastest speed which is in contrast with the findings from the current study. This study shows anger resulted in the second slowest gait speed after sadness. Although sample sizes were similar across the two studies there could be other factors that play a role in this discrepancy. The emotion elicitation methods in this study involved using VR and immersive video whilst Barliya et al. (2013) used memory recall as the elicitation method. Perhaps, the elicitation methods and specific intensity of the anger emotion felt may have played a role in modulating gait speed and this study, while successful in eliciting anger, may not have elicited the emotion at a high intensity. It is noteworthy that arousal levels in the anger condition were not purely concentrated in the “High” arousal level, rather the participants often also reported “Low” or “Med” arousal levels during this condition. Hence, anger may not have been elicited with the same intensity across participants which may have contributed to the results which showed the anger condition had the second slowest gait across the conditions.

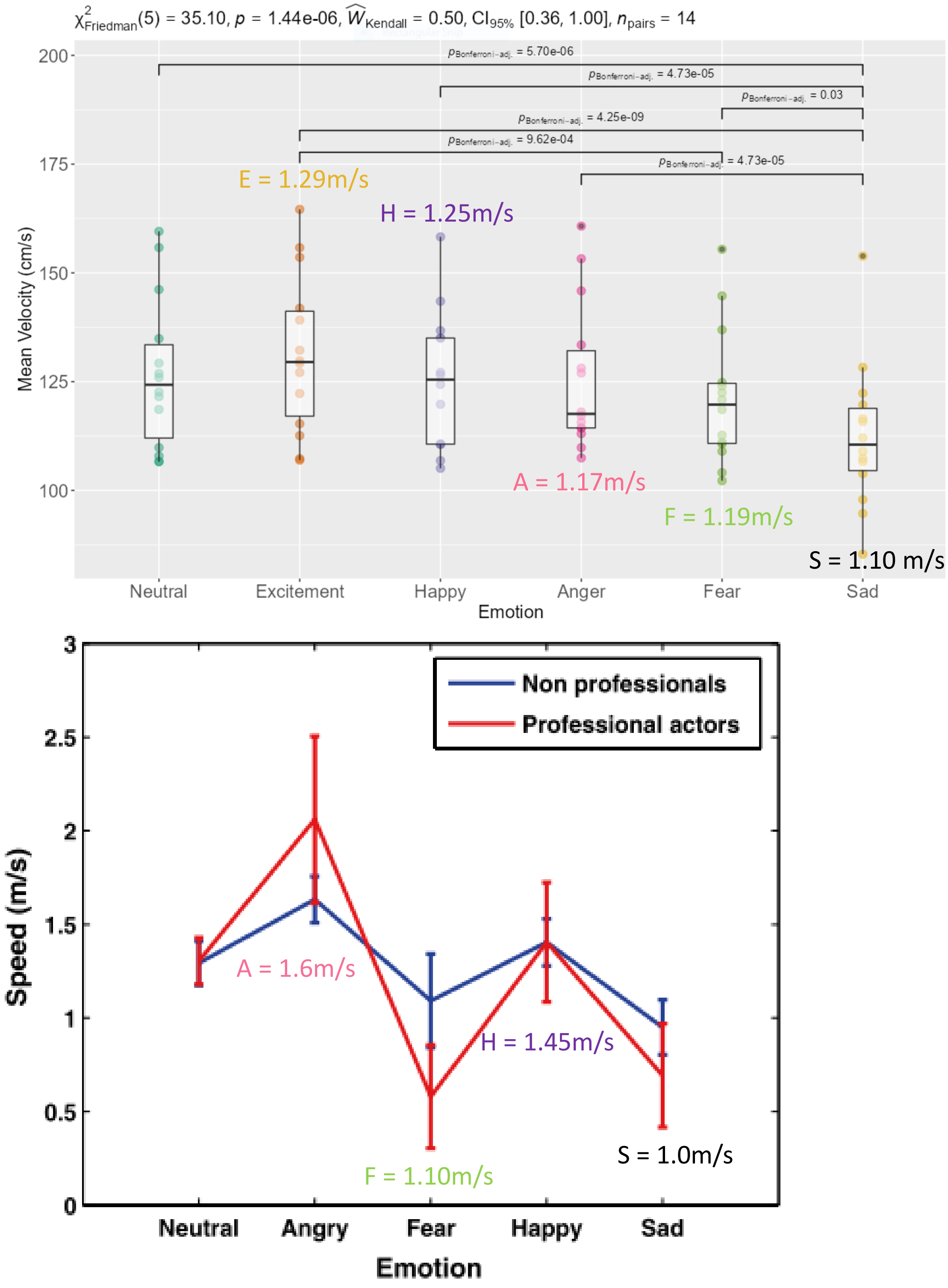

Figure 22: Displays comparisons between gait speed and emotional conditions from this study (top) and the results from Barliya et al. (2013) (bottom).

Gait changes in the rhythm domain, namely an increase in stance time and step time was found during the sadness condition compared to all other emotion conditions of happy, excited, fear, anger, and neutral. These results also are supported by previous literature (shown in figure 23), where the sadness condition showed an increased stance time duration when compared to other emotion conditions. Figure 23 showed that the sadness condition, in green, occupied a lower % swing phase duration (depicted by dashed lines) and thus the inverse is true where a larger % stance phase duration is seen (area outside the dashed lines) (Barliya et al., 2013). The increases in step times and stance times seen in the sadness condition may have also contributed to the decrease in gait speed and step length seen during the sadness condition compared to the other conditions.

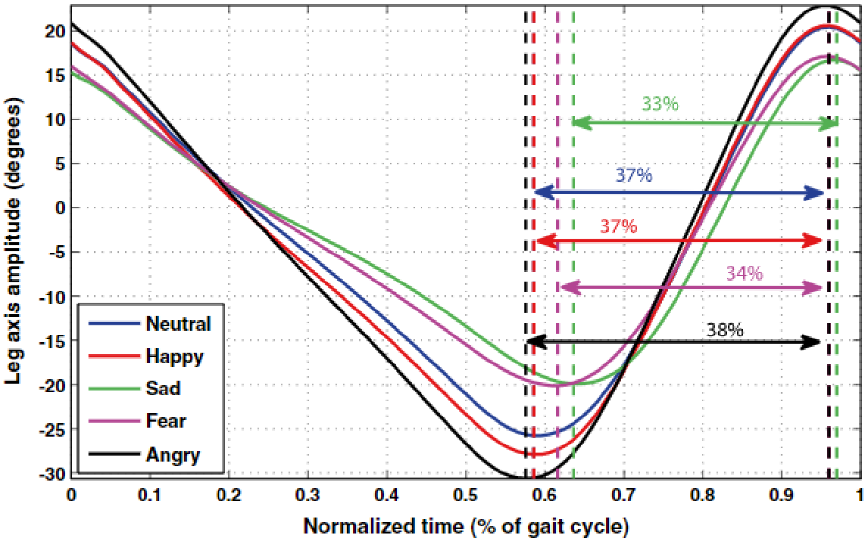

Figure 23: Displays Average leg-axis amplitude angle across the normalized gait cycle as reported by Barliya et al. (2013). Min values of the leg-axis amplitude represent toe-off, maximum values represent the heel contact points., The area within the dashed lines represents duration of swing phase duration and areas outside represent stance phase duration.

Despite sadness showing a decrease in velocity and step length compared to all other emotional conditions, a slight increase in swing time duration was observed during sadness condition (figure 14). However, this difference only existed between the conditions of sadness when compared with excitement and fear and no previous studies have shown similar results that show an increase in swing time during emotions of sadness. No other conditions were not found to be different from the sadness condition when comparing swing times. This slight increase in swing time duration could be attributed to overall decrease in pace. An overall decrease in gait speed and increase in step times and stance times (which are all observed during this condition) could also contribute to a slower but longer duration of swing time. Due to the nature of the slower walk in the sadness condition, the overall duration of the swing time increased.

The emotion of sadness, out of all emotional conditions showed the greatest impact on gait, resulting in decreases in both pace and all parameters within the rhythm domain. The implications of the findings from the first objective shows that whilst ordinary emotions of happy, excited, fear, anger may not influence gait significantly; sadness above all these emotions does show a large change in gait across different domains of gait. Comparing these findings to clinical research, current results show that decrease in parameters of gait speed in sadness were similar to decreases in gait speed when comparing healthy controls and patients with major clinical depression. Lemke et al. (2000) showed that patients with major depression had a reduction of ~0.23m/s in gait velocity compared to healthy controls. Results from this study showed that sadness condition resulted in a median gait velocity of 110.5cm/s (or 1.105 m/s) and neutral showed a gait velocity of 124.2 cm/s (or 1.242m/s) resulting in a difference of ~0.137m/s between neutral and sadness. However, this difference is greater when comparing excitement's velocity of 1.29 m/s to sadness' 1.10 m/s which results in a difference of ~0.19 m/s which is closer to the gait speed reduction seen in healthy controls vs patients with clinical depression. While it is not accurate to attempt to equate sadness with major depression, it is evident that emotions can have the capacity to meaningfully change gait behaviour. Therefore, the perhaps sadness, above all other emotion conditions should be considered a confound for future gait analysis and research in healthy and clinical populations.

To explain the changes in gait seen in these domains due to emotions, it is possible to leverage the advantages of both discrete and dimensional models. From a discrete perspective, the different emotional states of happy, excited, anger, fear, and sadness may be changing the cascade of neural activity as the participants watch the emotional stimuli. As Takakusaki (2013) displayed, while gait is an automatic process, there are still cortical and sub-cortical areas that affect gait before the cascade of neural activity reaches the spinal columns and central pattern generators. Deligianni et al. (2019) described the link between bipedal gait and emotional brain due to the common shared neural pathways and connections between multiple brain structures as well. Namely the shared structures of the PFC, BG and Thalamus which play a role in both emotion formation and gait is one possible reason why under different brain states, there might be changes in gait parameters. Although this explains *why* changes in gait could be present under different emotional states, it is still difficult to apply the discrete model to explain the directionality (or the *how)* of gait changes: i.e., why does gait speed decrease under sadness condition when compared to neutral or happy? It could be due some changes in the neural cascade or some different neural circuitry pathway that is activated during different emotional conditions that plays a role in these changes. But these are merely speculative and beyond the scope of this study. To gain further insight however, one might consider whether different models of emotions elaborate on a mechanistic explanation.

In terms of explaining a possible reason for the directionality of how different emotional states influence gait behaviour, the dimensional model may be a better fit to describe these results. It is important to note that the results from the current study are not to imply causality but rather evaluate low dimensional associations between different gait behaviour and the underlying dimensions of emotion such as Pleasure, Arousal and Dominance.

Whilst the reasoning using the discrete model to explain gait speed differences between happy and sad uses neural circuitry as its basis, using the dimensional model it is possible to look at the associative changes in PAD and possibly explain why these changes in gait speed are seen. Indeed, it was observed that as pleasure and dominance increased, so did gait parameters under the pace domain (gait speed and step length). As the sadness emotion represents low pleasure/ dominance and happiness represents high pleasure/dominance perhaps it is some change in the underlying dimensions of pleasure and dominance that is associated with gait changes in this direction when under the emotion condition of sadness and happiness.

Although the correlations between pleasure and dominance and the resultant gait parameters were weak, these results do give the dimensional model of emotions some advantage in describing the directionality of changes in gait due to change in underlying dimensions. These results are also supported by similar work that investigated the role of emotional dimensions on gait parameters. Results from previous work showed that increased pleasure (or valence) resulted in increases in gait speed, stride length, cadence etc. (Barda et al., 2018; Park et al., 2019) . Park et al. (2019) explained the increased gait speed, stride length, cadence etc. from pleasure due to the increased motivation to move that is seen in states of high pleasure. Similar results are reported by Naugle et al. (2011) who showed that increased gait initiation speed and motor movements were implicated when viewing pleasant stimuli once again supporting the idea that the dimension of pleasure may an influence on gait parameters. Thus, there may be a link between pleasure/dominance, motivation and ultimately motor behaviour that results in increased gait speed during states of higher pleasure/dominance. Emotional states and their underlying dimensions did influence gait in a myriad of different ways there are however remaining areas of gait that were unaffected by these emotional states.

4.2 Emotions did not Impact Variability or Postural Control

Although the discrete emotional conditions did not influence gait variability, nor postural control, there was a weak correlation between the dimension of arousal and dominance in gait variability (weak negative correlation for both arousal, dominance and stride velocity variability). Previous research showed that different mood disorders, namely increased anxiety in older adults with PD showed greater step-to-step variability (Ehgoetz Martens et al., 2018) and depression was shown to impact swing time variability (although this exists in the pace domain according to the 5-factor model of gait) (Dragašević-Mišković et al., 2021). Although these studies looked at older adults and clinical mood disorders such as anxiety and depression, it was expected that the emotions such as fear and sadness may generate similar changes to gait as anxiety and depression (respectively) and thus result in changes in variability; however, no such result was observed.

One possible explanation for the current results regarding the discrete emotions could be due to differences in age and disease condition. The sample in this study involved young healthy adults instead of a clinical population of older adults. It is possible that young healthy adults maintain a high degree of automaticity over their gait regardless of emotional conditions and mood disorders leading to fewer changes in their step-to-step variability of gait. Studies that have investigated dual tasking have shown that an increased cognitive load and cognitive demand consistently have a destabilizing effect on gait on older adults and thus impacting gait variability

(Hollman et al., 2007). Perhaps the emotions elicited in this study were not sufficient enough of a cognitive demand to cause changes in gait variability in young healthy adults. From a discrete model perspective, the neural circuitry which results in changes in gait variability may not be impacted by emotional states as much in younger adults, thus no changes in these parameters were seen. Supporting this reasoning, a recent study that examined affect, depression and gait showed that neither affective states nor depression showed any changes to gait parameters in young adults (Kumarid et al., 2021). It is possible, as Kumari et al. (2021) suggests, that affective changes in gait and gait changes due to mood disorders seen in older adults may be additionally influenced by age, decline of cognitive / executive function, and the comorbidities of additional physical health disorders from aging all of which are less likely to be present in a young population.

Yet it remains unclear whether the results of this study regarding emotional states and unchanging gait variability parameters would be the same for older adults or a clinical population. Older adults, and patients with depression may walk with increased rumination, resulting in increased cognitive load, and increased distractors as they walk—all which culminates in a modified gait pattern (Iqbal & Dar, 2015; Thomsen, 2006). This could potentially introduce more avenues for affective, particularly negative affective states like sadness to further alter gait behaviour in these population. Although not seen in the variability domain, sadness did show a large influence in young healthy adult gait in both pace and rhythm domains, it is possible that there may be an even more impactful effect of this emotion condition on older adults or a clinical population, possibly affecting gait variability. Further work is needed to study how emotional states affects older adults and those in clinical populations. Once again, future gait analysis may be implicated as everyday emotional states might play a greater role in influencing gait behaviour in these older and clinical populations. From a dimensional model perspective, the dimensions of dominance and arousal showed associations with in gait variability. It was hypothesized that the three dimensions of PAD would be negatively correlated with variability and the results confirmed that arousal and dominance but not pleasure was negatively correlated with gait variability. Specifically, arousal and dominance ratings showed a weak negative association with stride velocity variability (figure 18,21). Arousal and the influence of this dimension on gait variability from previous literature has found mixed results. One study that looked at PD patients showed that when patients walked in threatening situations which increased anxiety levels (and increased arousal measured by skin conductance), an increase in gait variability was observed (Ehgoetz Martens et al., 2018). However other mood disorder studies looking at depression found that gait variability was increased in patients with major depressive disorder which could be argued to have a lower level of overall arousal compared to healthy controls and agree with findings from this study (Hausdorff et al., 2004). It is possible that with increased arousal, there could be less conscious control of stride velocity resulting in a decrease in stride velocity variability, but there is a lack of literature studying gait variability and arousal in healthy adults to justify this conclusion.

Gait variability was not the only domain to show conflicting results within the arousal dimension relative to the findings of previous literature. In the current study, there were no associations found between arousal and aspects of pace or rhythm which have been reported previously. Yet, Park et al. (2019) showed that arousal was positively correlated with gait velocity, cadence, and stride time which implicate both the pace and rhythm domains. One possible explanation for this discrepancy could be the timing of the SAM ratings relative to the gait assessment. Since the SAM was reported immediately after watching the video and then gait was recorded, perhaps the effects of the emotional stimuli in the arousal dimension were diminished as the participant started walking. Although a participant would score high on arousal, their gait could revert to a more moderate state during the lead up to the walking trials. Thus, the results from the correlations conducted this study may not accurately indicate the true effect of arousal on gait and that previous literature has shown that arousal does have an impact on gait beyond just the variability domain. Future research is needed to investigate this possible temporal discrepancy between arousal reporting and walking trials to measure the effects of arousal on gait. Perhaps a more interactive VR stimuli could be used in the future to elicit different levels of arousal while the participant is walking to determine how arousal modulates real-time gait behaviour.

Overall, the implications of these results show that while the discrete model may provide a simplistic description of emotion-induced gait changes within the pace and rhythm domains, the dimensional model highlighted associated changes to gait (albeit weak correlations) that relate to unique dimensions of emotion rather than independent and discrete emotions perse. The mechanistic explanation for changes in gait due to emotion remains largely unexplored however the dimensional model is more in favour of a possible neurobiological / neurochemical basis for the changes in gait due to emotion.

4.3 Neurobiological Basis for Gait and Emotion

As Takusaki (2013) reported, the modulators of gait are quite complex, and many different regions of the cortical and subcortical brain are involved in gait and gait patterns. This work and previous literature in this field all in some way contribute to the large theoretical question which is “what is the *mechanism* that changes gait due to emotional states?”. The dimensional model of PAD touches on some aspects of these systems influencing gait; pleasure could increase motivation which could implicate the emotional process and the limbic system causing changes in gait from this stream as it modulates the neural cascade (figure 1) (Park et al., 2019). Arousal could also lead to an increase in motivation and has shown to influence gait initiation which could implicate the volitional process in gait thus modulate gait behaviour from this stream(Naugle et al., 2011; Park et al., 2019). However, perhaps a more specific neurobiological framework could also be used to explain differences in emotion and gait. Using Lovheim's model as a framework of emotions, it could be argued that changes in gait result from a change in the concentration of neurotransmitters (with norepinephrine, dopamine, and serotonin being the three orthogonal neurotransmitters) in the brain when experiencing a specific emotion (Lövheim, 2012). From PD patients suffering gait deficits due to change in dopamine in the brain (Ehgoetz Martens et al., 2014) and patients suffering from major depression due to serotonergic deficits (Price et al., 2009) there exists evidence that these neurotransmitters do play a motor role in the body. It's with this reasoning that it may be possible gait changes observed during emotions of excitement and happiness are different form gait observed during fear and sadness due to change in the levels of dopamine, noradrenaline, and serotonin. For example, during fear and sadness, there could be a reduction of serotonin in the brain, which is typically observed in patients with major depression resulting in gait with slower velocity, increased stance times and decreased stride/step lengths as shown by Lemke et al. (2000). Future work could investigate this avenue of emotion and see whether gait changes could be explained by the changes in neurobiological chemicals and monoamine neurotransmitters in the brain.

4.4 Strengths, Limitations, and Future Directions

The strengths of this study lie in its within-subjects design when evaluating changes in gait from discrete emotions. Emotion elicitation from the immersive video/VR environment and responses from the subjects were also favorable as it showed success in eliciting the target emotions. Finally, this study also used healthy non-actors for its sample which enables a more accurate interpretation of the results onto the general effects of emotion and gait. As it was most accurate to use a within-subjects design to investigate emotion and gait, the main limitation for this study stems from the low sample size of 14 when performing the Friedman's tests. Although there was a moderate to strong effect sizes of the emotional conditions across some measures of gait (such as velocity and stance time), having a larger sample size could possibly result in an increased power of the current study.

In terms of emotion elicitation, while VR and video was a valid way to elicit emotions, the videos remain still somewhat subjective and are prone to resulting in different interpretations causing inter-participant discrepancy in the SAM reporting and their own self-reported emotions. The usage of the 14-person "concentrated" emotional dataset was an attempt to address this discrepancy in emotional response and reduce the inter-participant variability in report of SAMs and emotional reports. Perhaps, with a more physiological measure of some of these dimensions, for example using EDA to measure arousal levels, there would be a better indication of how aroused a participant was feeling and then compare how gait behaviour correlated with this dimension.

Finally, this study mainly looked at stepping kinematics when evaluating gait differences in emotional states while body posture and whole-body kinematics was largely ignored.

Certainly, from the work of Halovic & Kroos (2018), Karg et al. (2009), Barliya et al. (2013), and Roether et al. (2009) it is reported that body kinematics change substantially as a result of gait. For a better understanding of how emotions affect gait, and how emotional dimensions affect gait, a deeper look into whole body movements is essential.

Future work could also perhaps explore further the neurobiological basis of emotions and probe how different concentrations of monoamine neurotransmitters may play a role in modulating gait behaviour using Lovheim's model as a framework (Lövheim, 2012).

4.5 Conclusion

The primary objective in this study was to examine how emotional states changed gait parameters using the 5-factor model in a non-actor population. The main findings from this study show that emotions of sadness, above all other emotions tends to show the largest discrepancy in gait when compared to other emotions and a neutral condition. The domains of variability and postural control were not influenced by changes in emotional states in young adults, but pace and rhythm were impacted by emotional states.

From a dimensional perspective of emotions, pleasure and dominance had greater influence in gait compared to arousal as it related to spatio-temporal parameters of gait. Arousal, while shown in the past to affect motor behaviour and gait initiation did not show any significant results in any variables except stride velocity variability, where a negative correlation was seen. Overall, this work builds upon previous affect and gait literature and furthers our understanding of how emotional states and different dimensions of emotions may change and influence gait behavior. It is recommended that future research in both clinical and experimental settings should possibly consider evaluating the emotional state of an individual, particularly the emotion of sadness as it showed to have a large influence in young healthy adult gait.

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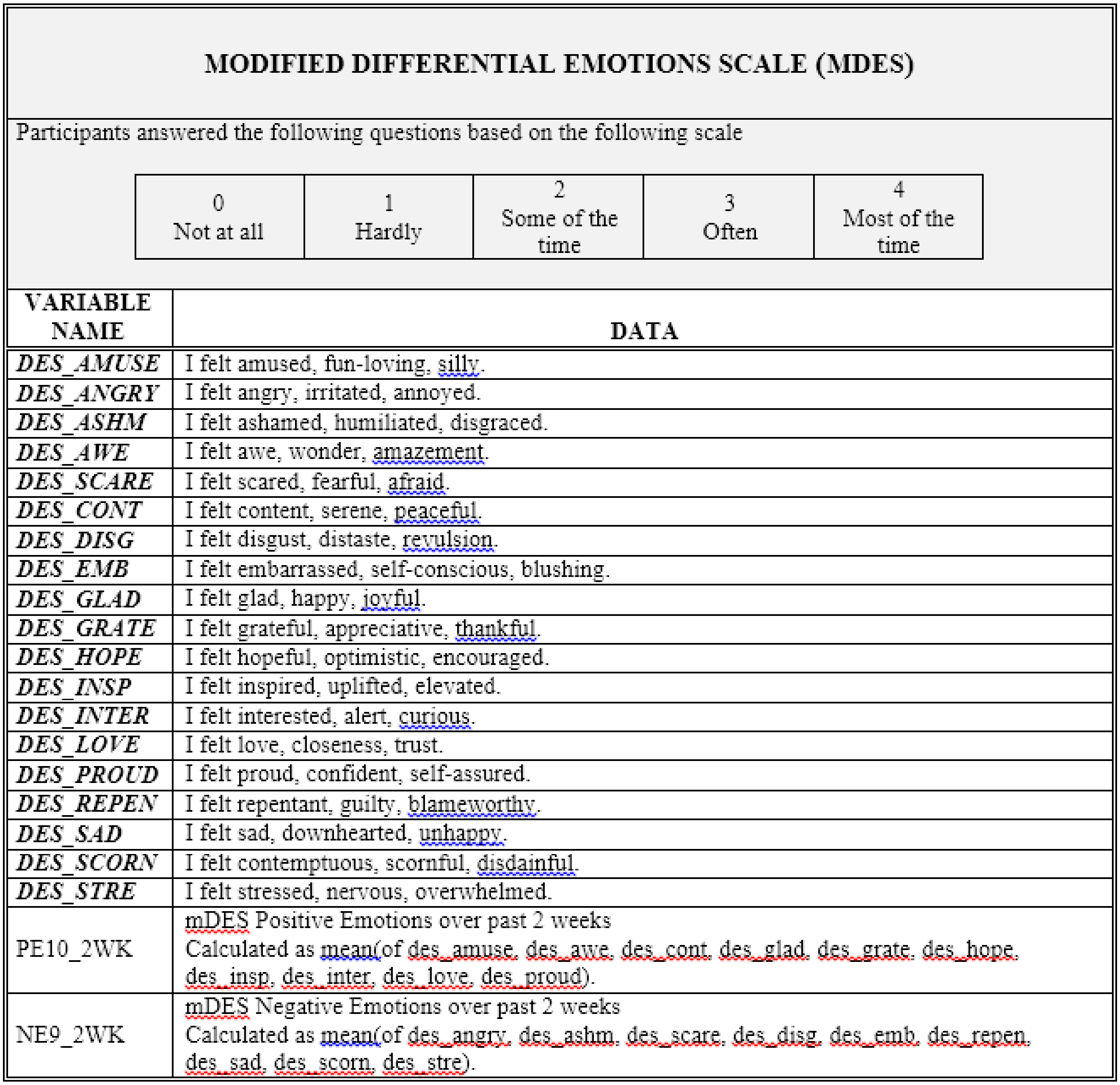
Appendix A – Questionnaires



MODIFIED DIFFERENTIAL EMOTIONS SCALE (MDES)

Participants answered the following questions based on the following scale

0 Not at all	1 Hardly	2 Some of the time	3 Often	4 Most of the time

VARIABLE NAME	DATA
DES_AMUSE	I felt amused, fun-loving, silly.
DES_ANGRY	I felt angry, irritated, annoyed.
DES_ASHM	I felt ashamed, humiliated, disgraced.
DES_AWE	I felt awe, wonder, amazement.
DES_SCARE	I felt scared, fearful, afraid.
DES_CONT	I felt content, serene, peaceful.
DES_DISG	I felt disgust, distaste, revulsion.
DES_EMB	I felt embarrassed, self-conscious, blushing.
DES_GLAD	I felt glad, happy, joyful.
DES_GRATE	I felt grateful, appreciative, thankful.
DES_HOPE	I felt hopeful, optimistic, encouraged.
DES_INSP	I felt inspired, uplifted, elevated.
DES_INTER	I felt interested, alert, curious.
DES_LOVE	I felt love, closeness, trust.
DES_PROUD	I felt proud, confident, self-assured.
DES_REPEN	I felt repentant, guilty, blameworthy.
DES_SAD	I felt sad, downhearted, unhappy.
DES_SCORN	I felt contemptuous, scornful, disdainful.
DES_STRE	I felt stressed, nervous, overwhelmed.
PE10_2WK	mDES Positive Emotions over past 2 weeks Calculated as mean(of des_amuse, des_awe, des_cont, des_glad, des_grate, des_hope, des_insp, des_inter, des_love, des_proud).
NE9_2WK	mDES Negative Emotions over past 2 weeks Calculated as mean(of des_angry, des_ashm, des_scare, des_disg, des_emb, des_repen, des_sad, des_scorn, des_stre).

Supplementary Figures

A1 – Friedman ANOVA Raw Pleasure and Emotional Conditions

Figure A1: Displays the Raw Pleasure values across the emotion conditions from the concentrated emotional dataset. Subtitle displays the results of the Friedman ANOVA.

A2 - Pairwise Comparisons – Raw Pleasure Ratings

group1	group2	statistic	p.value	sig	p.adjust.method
Anger	Fear	1.110935	1	ns	Bonferroni
Anger	Sad	4.999209	6.93E-05	*	Bonferroni
Excitement	Anger	13.88669	6.05E-20	*	Bonferroni
Excitement	Fear	14.99763	1.31E-21	*	Bonferroni
Excitement	Happy	3.517962	0.011987	*	Bonferroni
Excitement	Sad	18.8859	6.50E-27	*	Bonferroni
Fear	Sad	3.888274	0.003596	*	Bonferroni
Happy	Anger	17.40465	5.54E-25	*	Bonferroni
Happy	Fear	18.51559	1.93E-26	*	Bonferroni
Happy	Sad	22.40386	4.22E-31	*	Bonferroni
Neutral	Anger	9.257794	2.62E-12	*	Bonferroni
Neutral	Excitement	4.628897	0.000271	*	Bonferroni
Neutral	Fear	10.36873	3.10E-14	*	Bonferroni
Neutral	Happy	8.146859	2.40E-10	*	Bonferroni
Neutral	Sad	14.257	1.66E-20	*	Bonferroni

Figure A2: Displays the results of the Durbin-Conover test pairwise comparisons of pleasure ratings across emotion conditions alongside Bonferroni adjusted p values.

A3- Friedman ANOVA Raw Arousal and Emotional Conditions

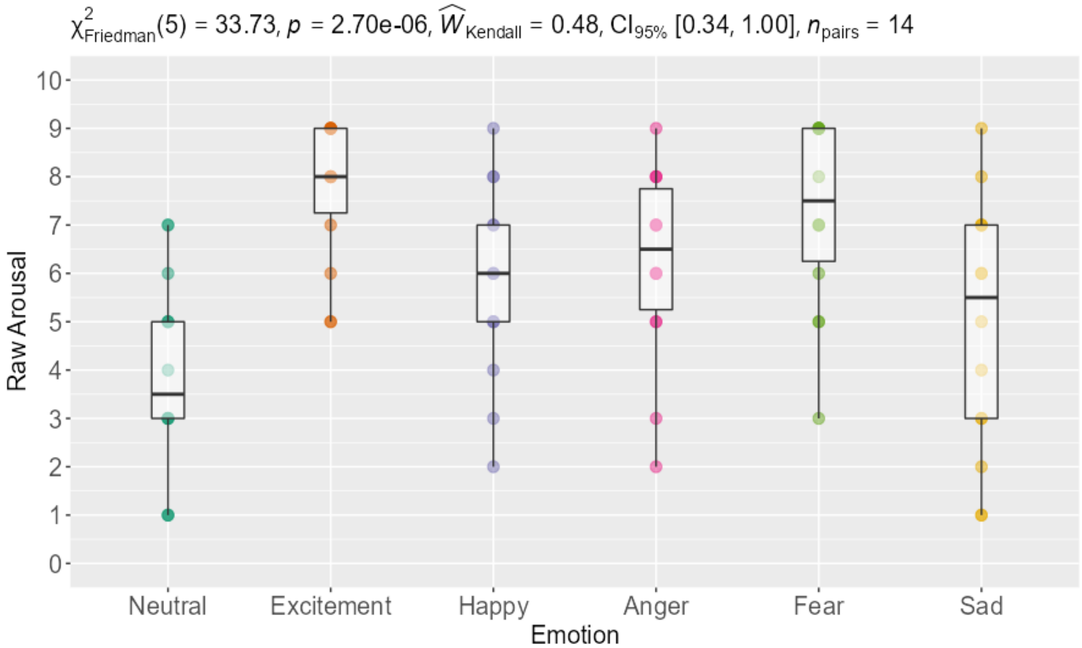


Figure A3: Displays the Raw Arousal values across the emotion conditions from the concentrated emotional dataset. Subtitle displays the results of the Friedman ANOVA.

A4 - Pairwise Test Comparisons – Raw Arousal Ratings

group1	group2	statistic	p.value	sig	p.adjust.method
Anger	Fear	2.10487	0.587595	ns	Bonferroni
Anger	Sad	1.964545	0.806171	ns	Bonferroni
Excitement	Anger	2.666168	0.145048	ns	Bonferroni
Excitement	Fear	0.561299	1	ns	Bonferroni
Excitement	Happy	3.297629	0.023752	*	Bonferroni
Excitement	Sad	4.630713	0.00027	*	Bonferroni
Fear	Sad	4.069414	0.001951	*	Bonferroni
Happy	Anger	0.631461	1	ns	Bonferroni
Happy	Fear	2.73633	0.120036	ns	Bonferroni
Happy	Sad	1.333084	1	ns	Bonferroni
Neutral	Anger	3.858927	0.003966	*	Bonferroni
Neutral	Excitement	6.525095	1.78E-07	*	Bonferroni
Neutral	Fear	5.963797	1.68E-06	*	Bonferroni
Neutral	Happy	3.227467	0.029371	*	Bonferroni
Neutral	Sad	1.894383	0.93937	ns	Bonferroni

Figure A4: Displays the results of the Durbin-Connover test pairwise comparisons of arousal ratings across emotion conditions alongside Bonferroni adjusted p values.

A5 - Friedman ANOVA Raw Dominance and Emotional Conditions

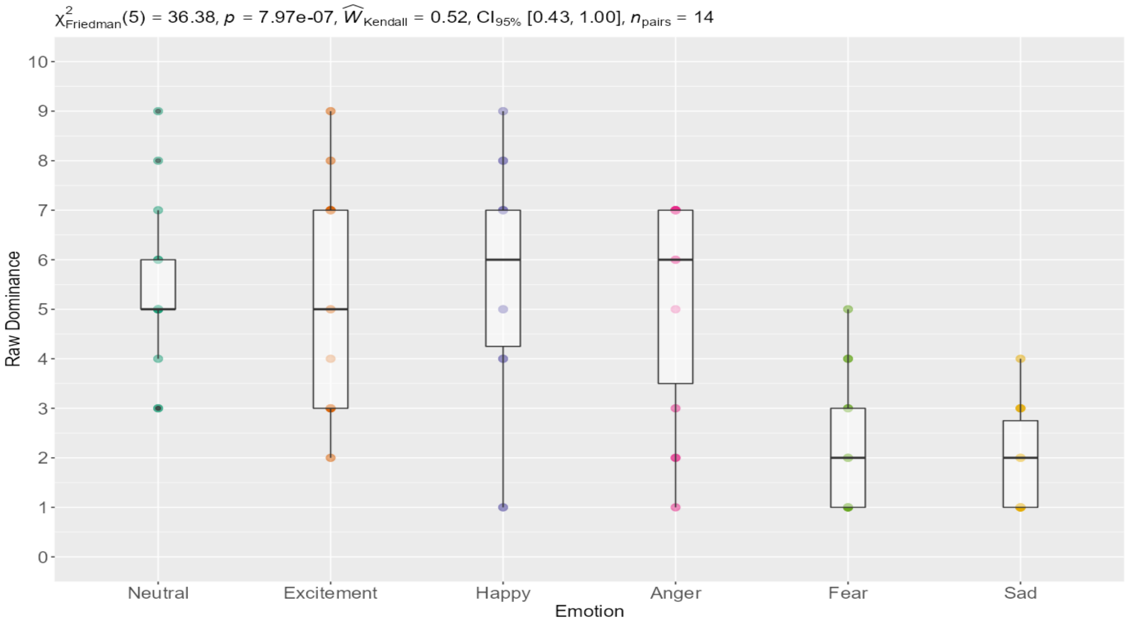


Figure A5: Displays the Raw Dominance values across the emotion conditions from the concentrated emotional dataset. Subtitle displays the results of the Friedman ANOVA.

A6 - Pairwise Test Comparisons – Raw Dominance Ratings

group1	group2	statistic	p.value	sig	p.adjust.method
Anger	Fear	4.149688	0.001481	*	Bonferroni
Anger	Sad	5.096108	4.81E-05	*	Bonferroni
Excitement	Anger	0.436809	1	ns	Bonferroni
Excitement	Fear	4.586497	0.000316	*	Bonferroni
Excitement	Happy	0.364008	1	ns	Bonferroni
Excitement	Sad	5.532918	9.06E-06	*	Bonferroni
Fear	Sad	0.94642	1	ns	Bonferroni
Happy	Anger	0.800817	1	ns	Bonferroni
Happy	Fear	4.950505	8.31E-05	*	Bonferroni
Happy	Sad	5.896925	2.18E-06	*	Bonferroni
Neutral	Anger	0.582412	1	ns	Bonferroni
Neutral	Excitement	0.145603	1	ns	Bonferroni
Neutral	Fear	4.732101	0.000186	*	Bonferroni
Neutral	Happy	0.218405	1	ns	Bonferroni
Neutral	Sad	5.678521	5.14E-06	*	Bonferroni

Figure A6: Displays the results of the Durbin-Conover test pairwise comparisons of arousal ratings across emotion conditions alongside Bonferroni adjusted p values.

A7 Raw Pleasure, Arousal and Dominance values across emotions

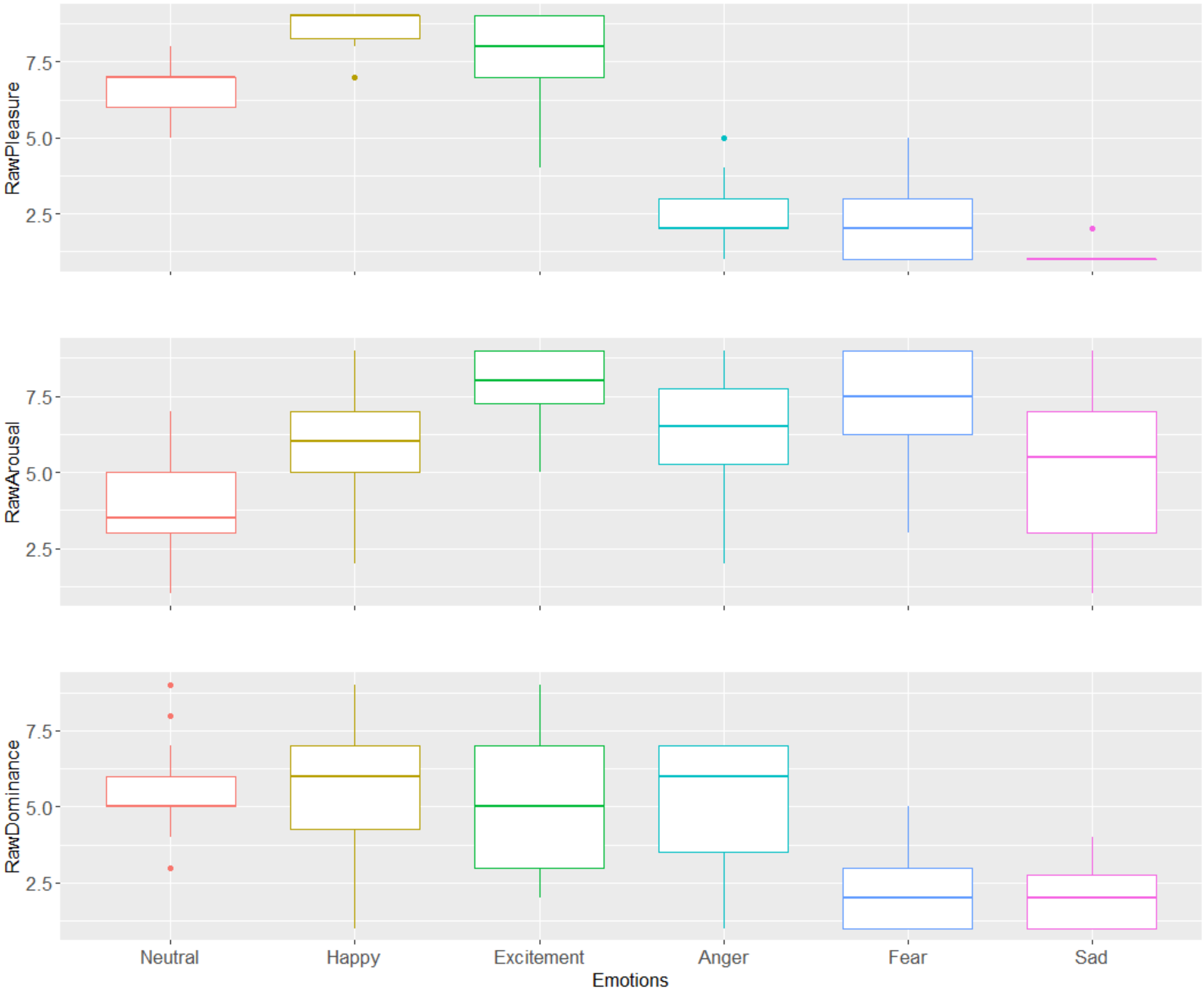
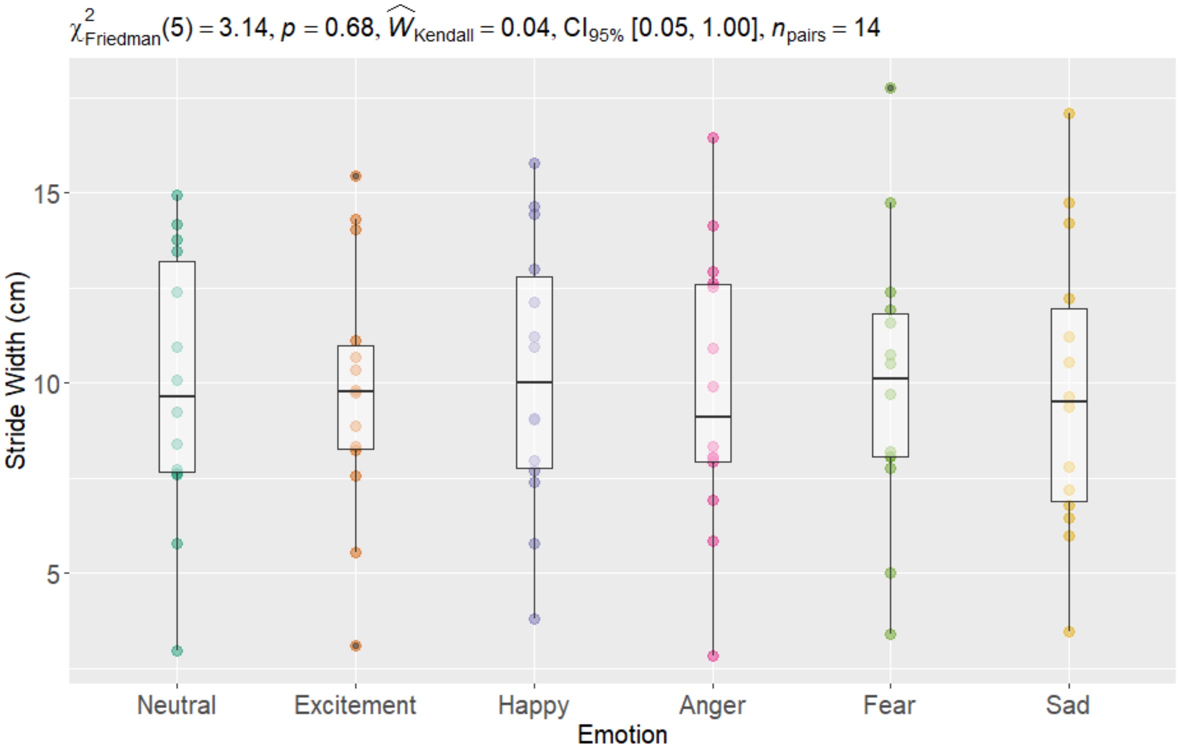


Figure A7: Shows the Raw Pleasure, Arousal and Dominance scores in the n=14 subset of participants across all emotional conditions. Two unique groups of emotional clusters are observed in the Raw Pleasure dimension where the neutral emotional state is closer to happiness and excitement.

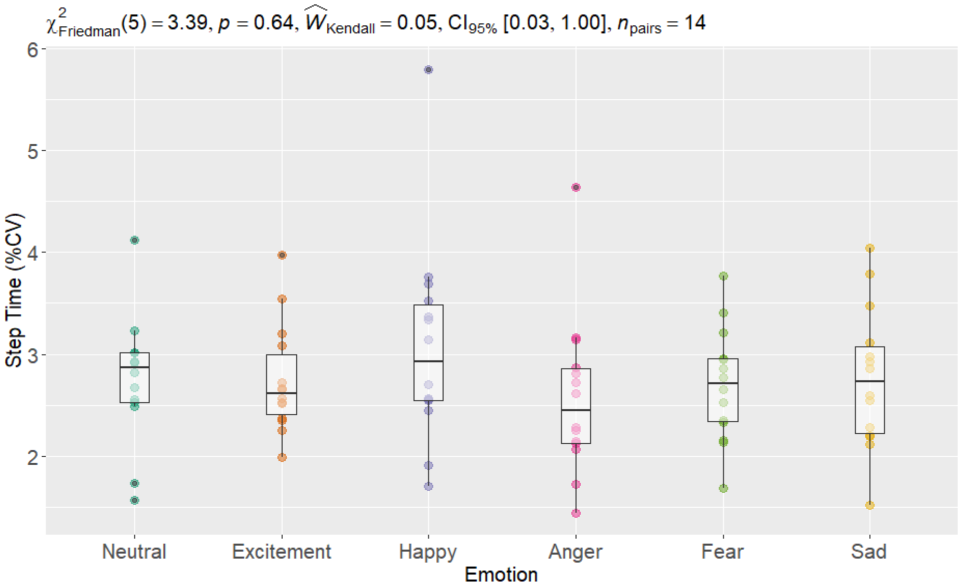
A8 Friedman ANOVA – Stride width across emotion conditions



$\chi^2_{\text{Friedman}}(5) = 3.14$, $p = 0.68$, $\widehat{W}_{\text{Kendall}} = 0.04$, $\text{CI}_{95\%}$ [0.05, 1.00], $n_{\text{pairs}} = 14$

Figure A8: Shows the Friedman ANOVA results and boxplot of each emotional condition and stride width (cm) for each emotion.

A9 Friedman ANOVA- Step time variability across emotion conditions



$\chi^2_{\text{Friedman}}(5) = 3.39$, $p = 0.64$, $\widehat{W}_{\text{Kendall}} = 0.05$, $\text{CI}_{95\%}$ [0.03, 1.00], $n_{\text{pairs}} = 14$

Figure A9: Shows the Friedman ANOVA results and boxplot of each emotional condition and step time %CV (s) for each emotion.

A10 Friedman ANOVA – Swing time variability across emotion conditions

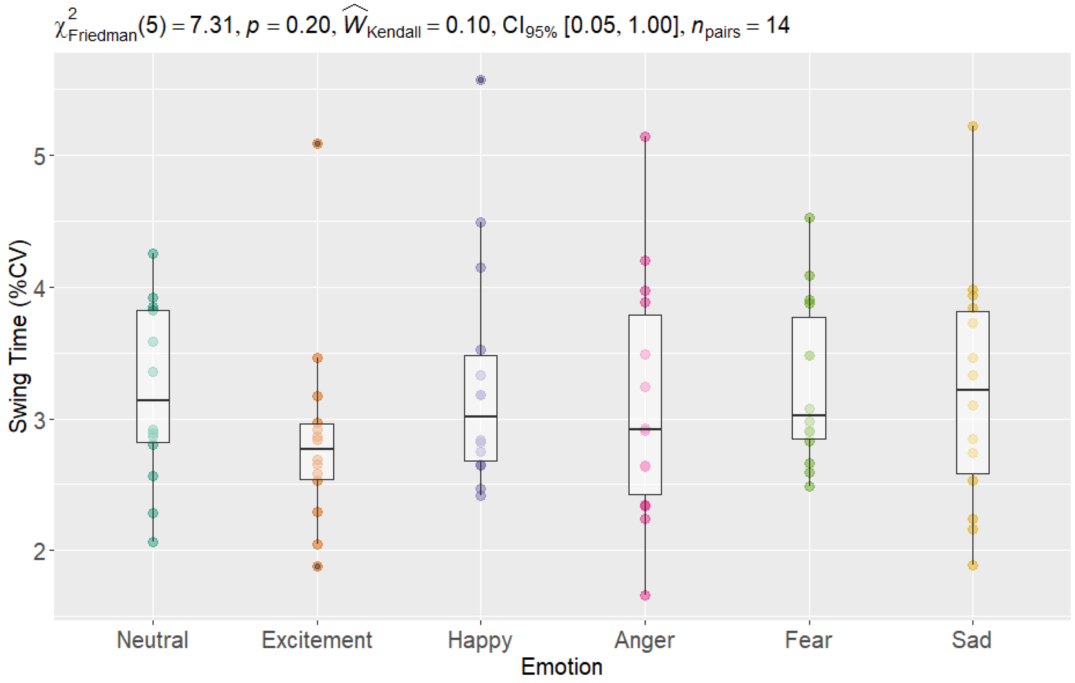


Figure A10: Shows the Friedman ANOVA results and boxplot of each emotional condition and swing time %CV (s) for each emotion.

A11 Friedman ANOVA- Step length variability across emotion conditions

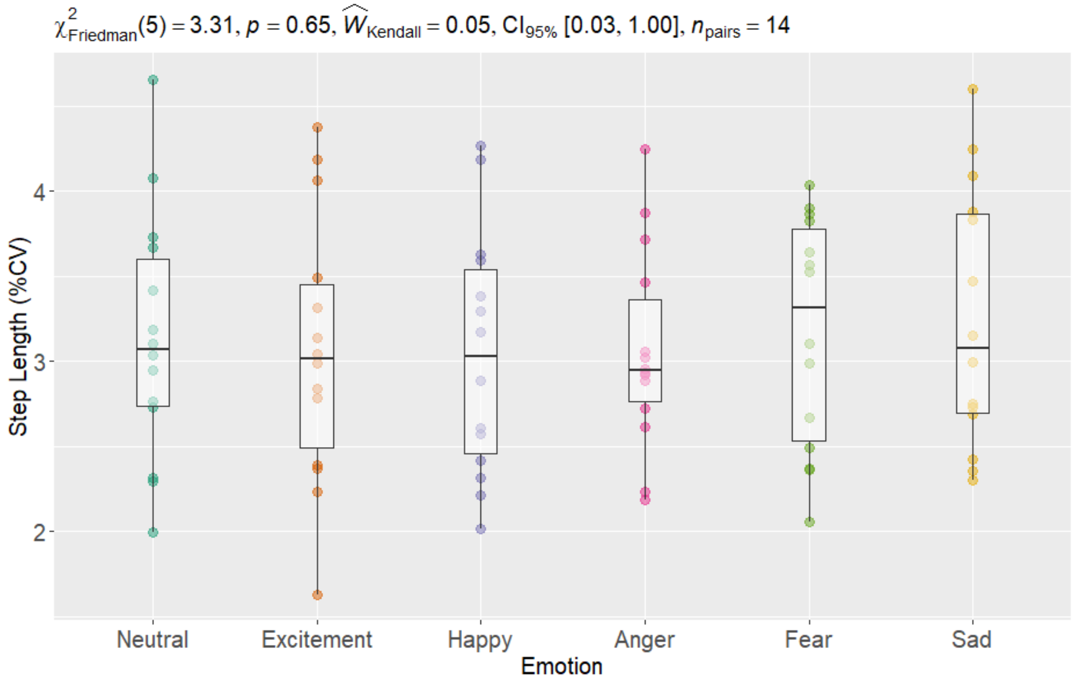


Figure A11: Shows the Friedman ANOVA results and boxplot of each emotional condition and step length %CV (cm) for each emotion.

A12 Friedman ANOVA – Step width variability across emotion conditions

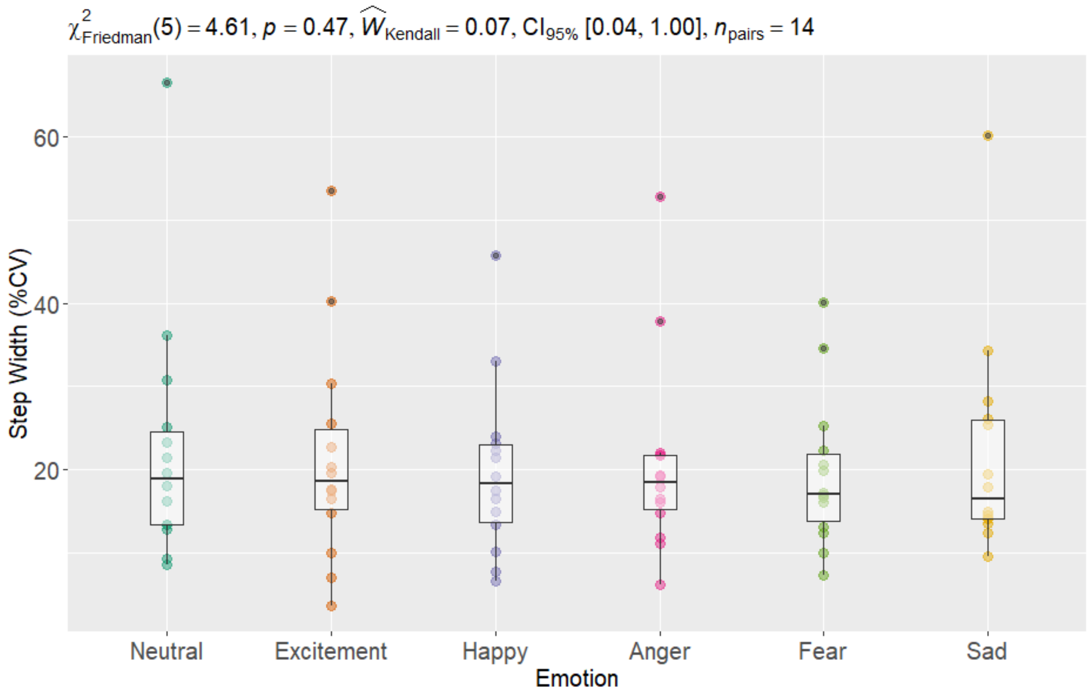


Figure A12: Shows the Friedman ANOVA results and boxplot of each emotional condition and step width %CV (cm) for each emotion.

A13 Friedman ANOVA – Stride velocity variability across emotion conditions

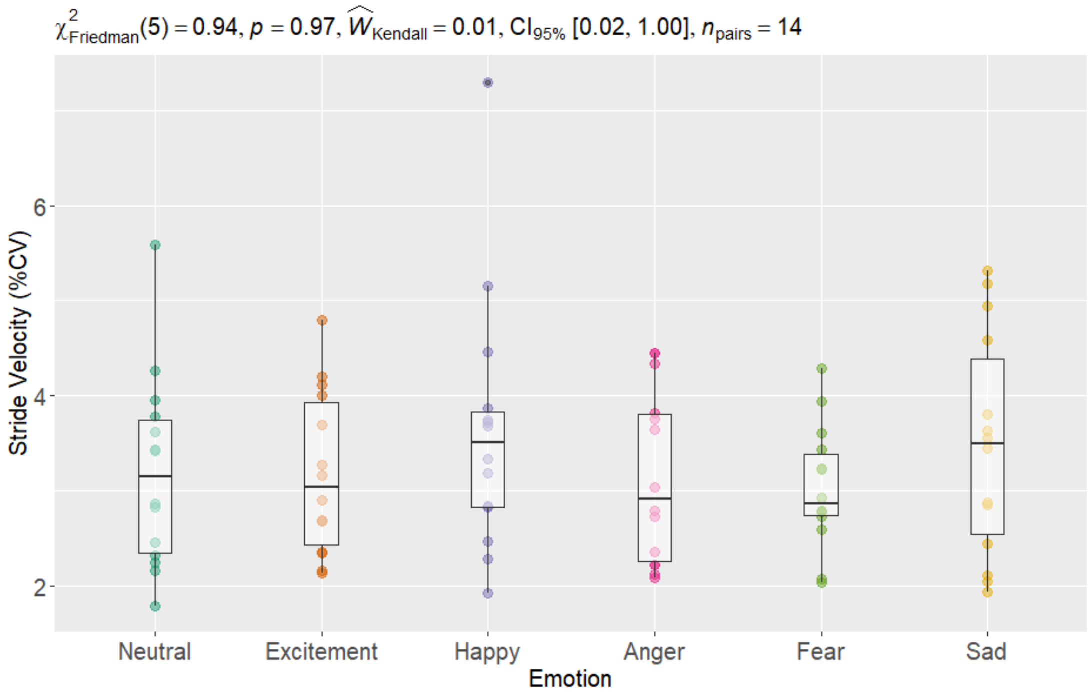


Figure A13: Shows the Friedman ANOVA results and boxplot of each emotional condition and stride velocity %CV (cm/s) for each emotion.

A14 Spearman Correlation – Pleasure & Pace

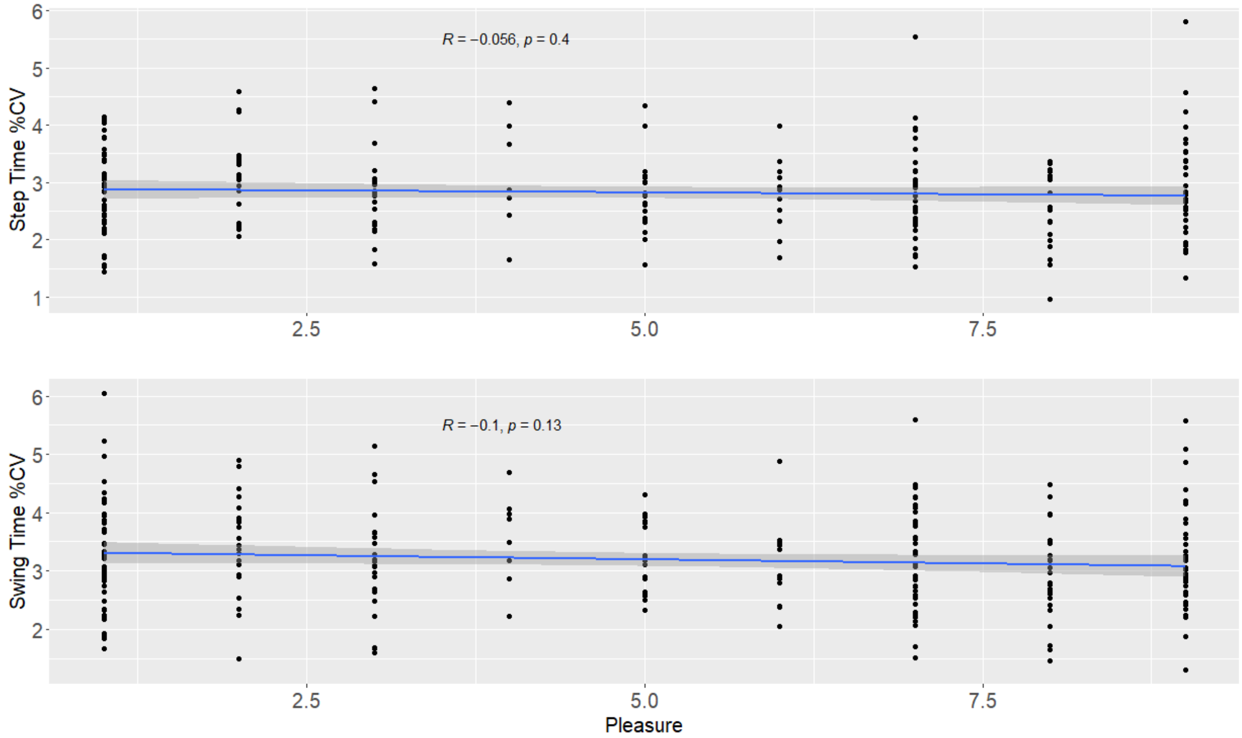


Figure A14: Shows the spearman correlations of the domain of Pleasure across the pace domain variables of step time %CV (top) and swing time %CV (bottom). R represents the spearman's rho value.

A15 Spearman Correlation – Pleasure & Rhythm

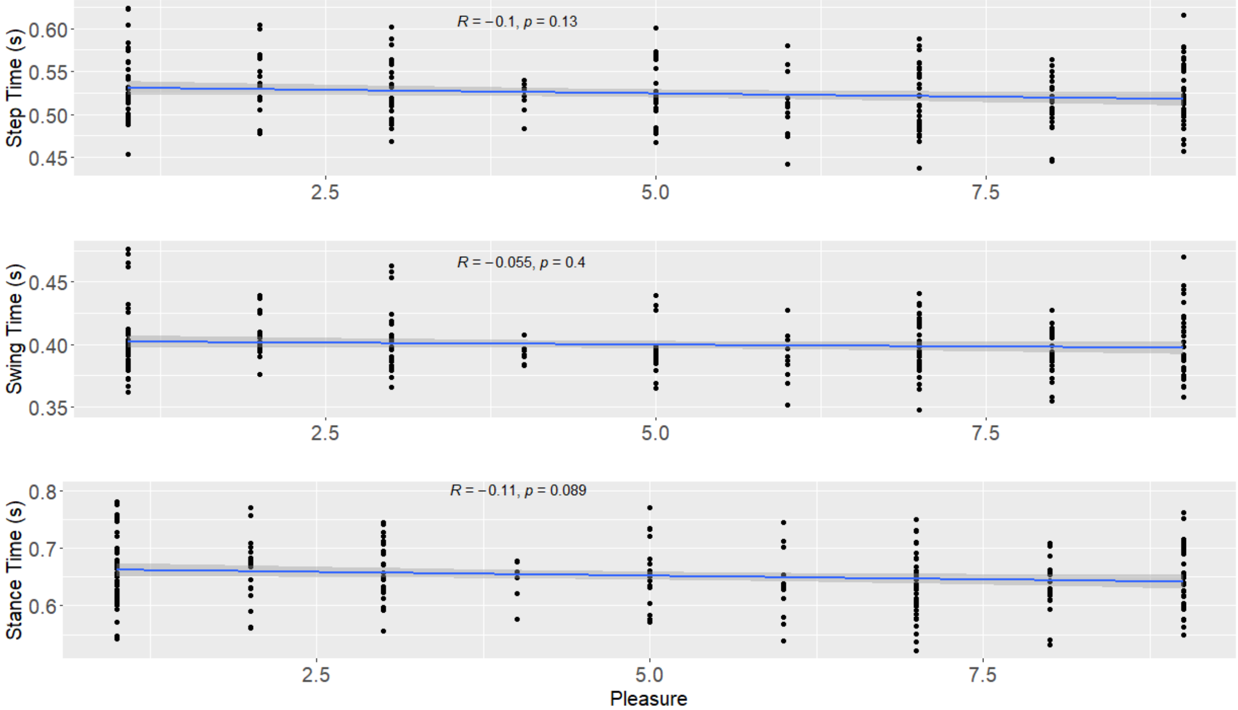


Figure A15: Shows the spearman correlations of the domain of Pleasure across the rhythm domain variables of step time (s) (top), swing time (s) (middle) and stance time (s) (bottom). R represents the spearman's rho value.

A16 Spearman Correlation – Pleasure & Variability

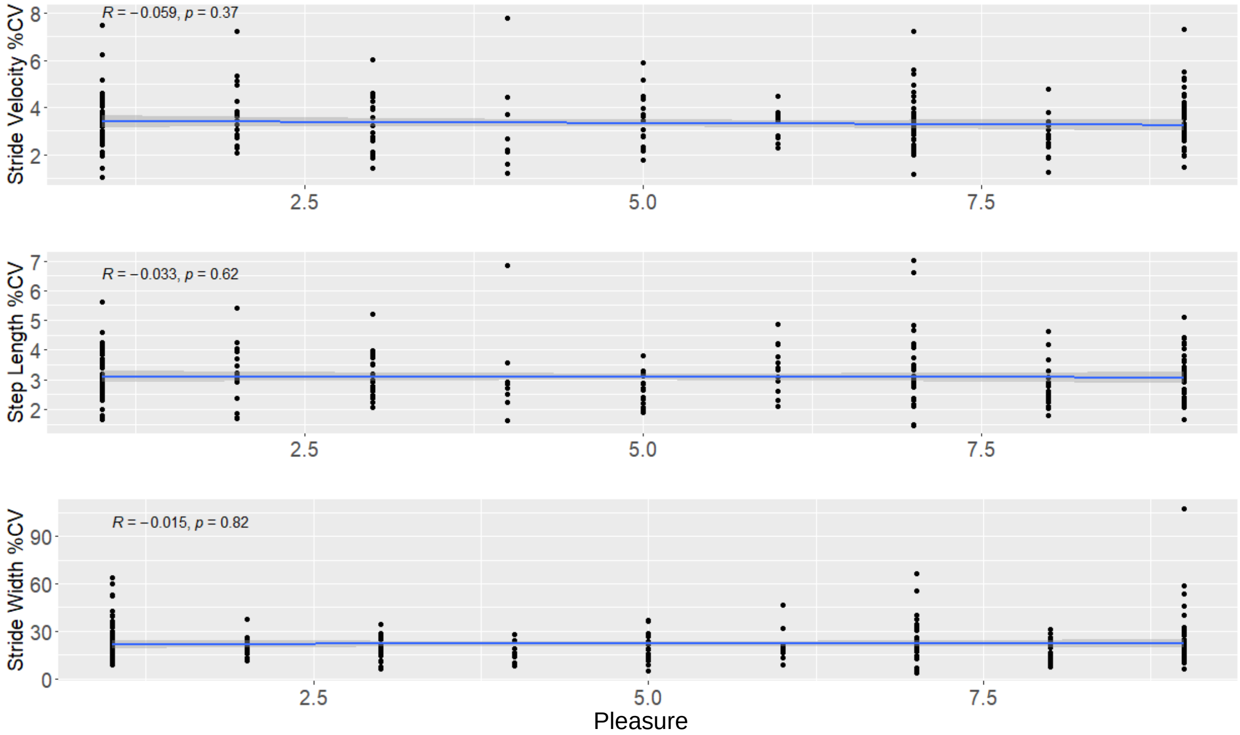


Figure A16: Shows the spearman correlations of the domain of Pleasure across the variability domain variables of stride velocity %CV (cm/s) (top), step length %CV (cm) (middle) and stride width %CV (cm) (bottom). R represents spearman's rho.

A17 Spearman Correlation – Pleasure & Postural Control

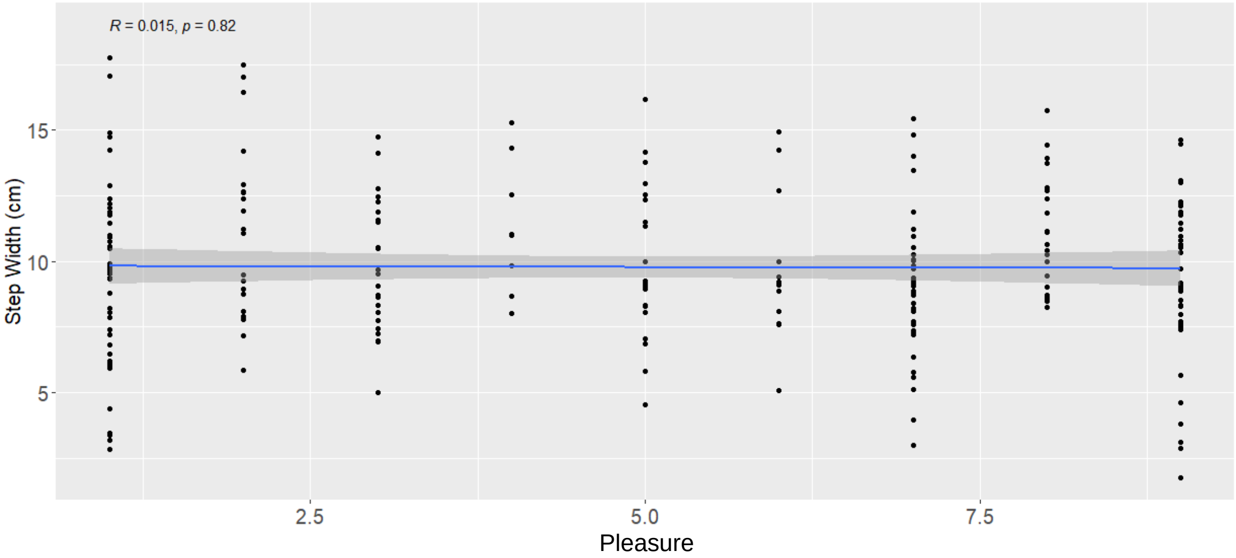


Figure A17: Shows the spearman correlations of the domain of Pleasure across the postural control domain variable of step width (cm). R represents spearman's rho.

A18 Spearman Correlation – Arousal & Pace

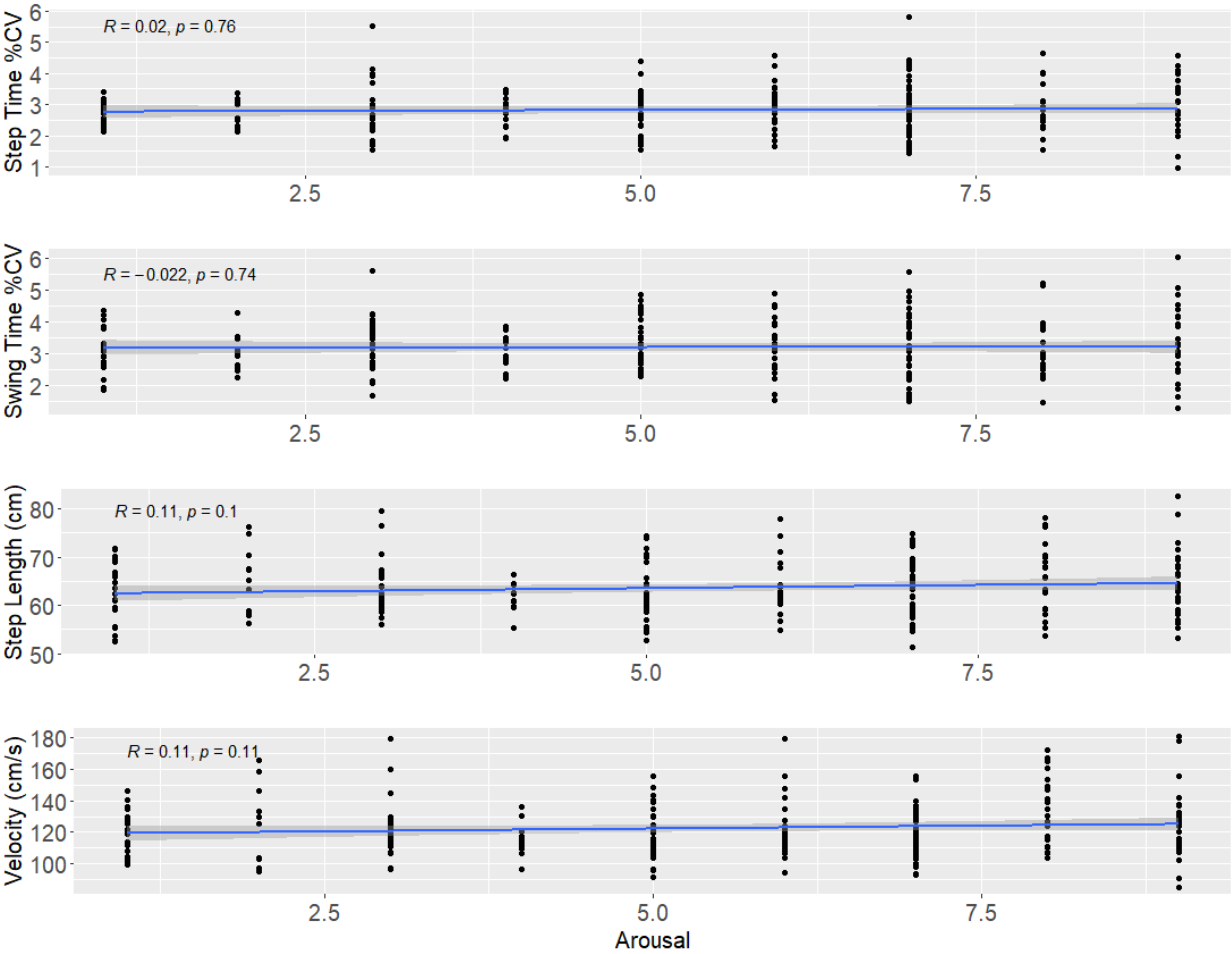


Figure A18: Shows the spearman correlations of the domain of Arousal across the pace domain variables of step time %CV (top) swing time %CV (middle-top), step length (cm) (middle-bottom), and velocity (cm/s) (bottom). R represents the spearman's rho value.

A19 Spearman Correlation – Arousal & Rhythm

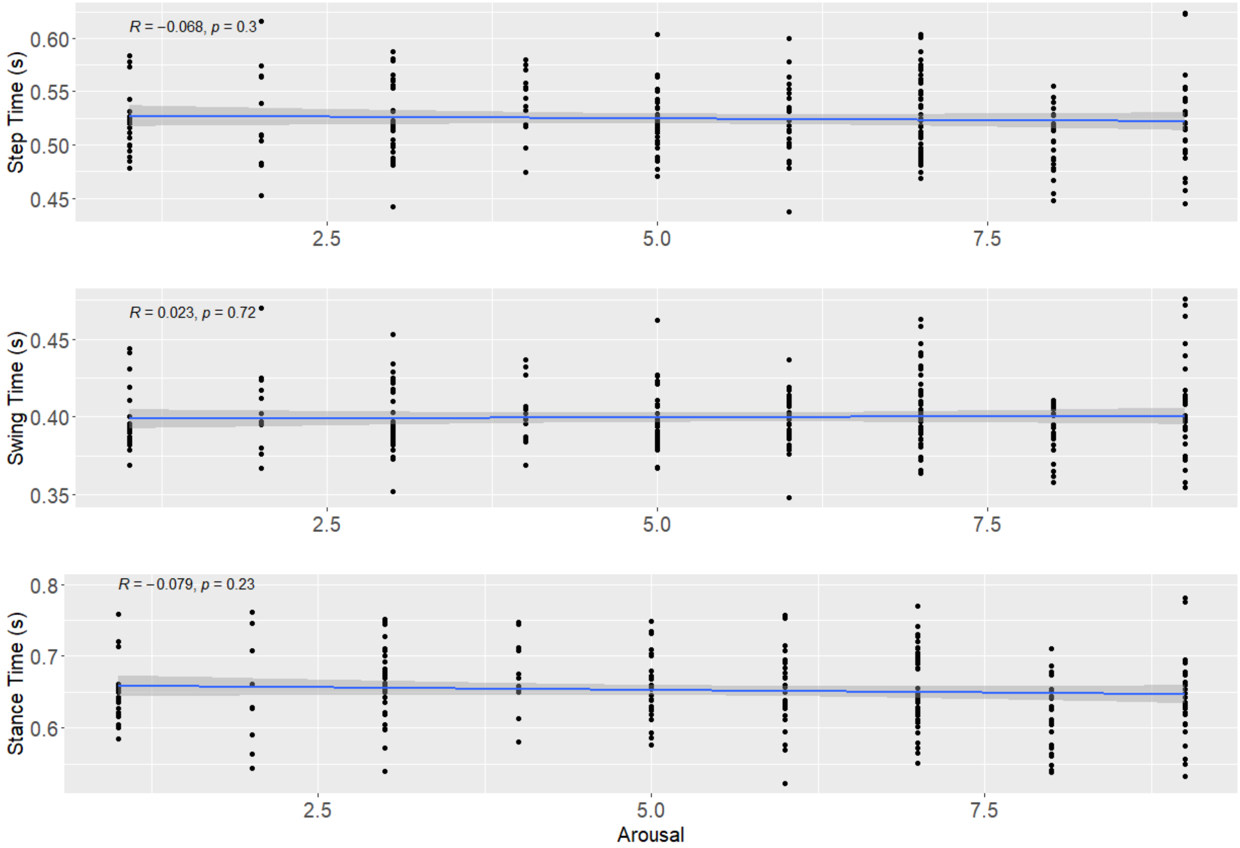


Figure A19: Shows the spearman correlations of the domain of Arousal across the rhythm domain variables of step time (s) (top), swing time (s) (middle) and stance time (s) (bottom). R represents the spearman's rho value.

A20 Spearman Correlation – Arousal & Variability

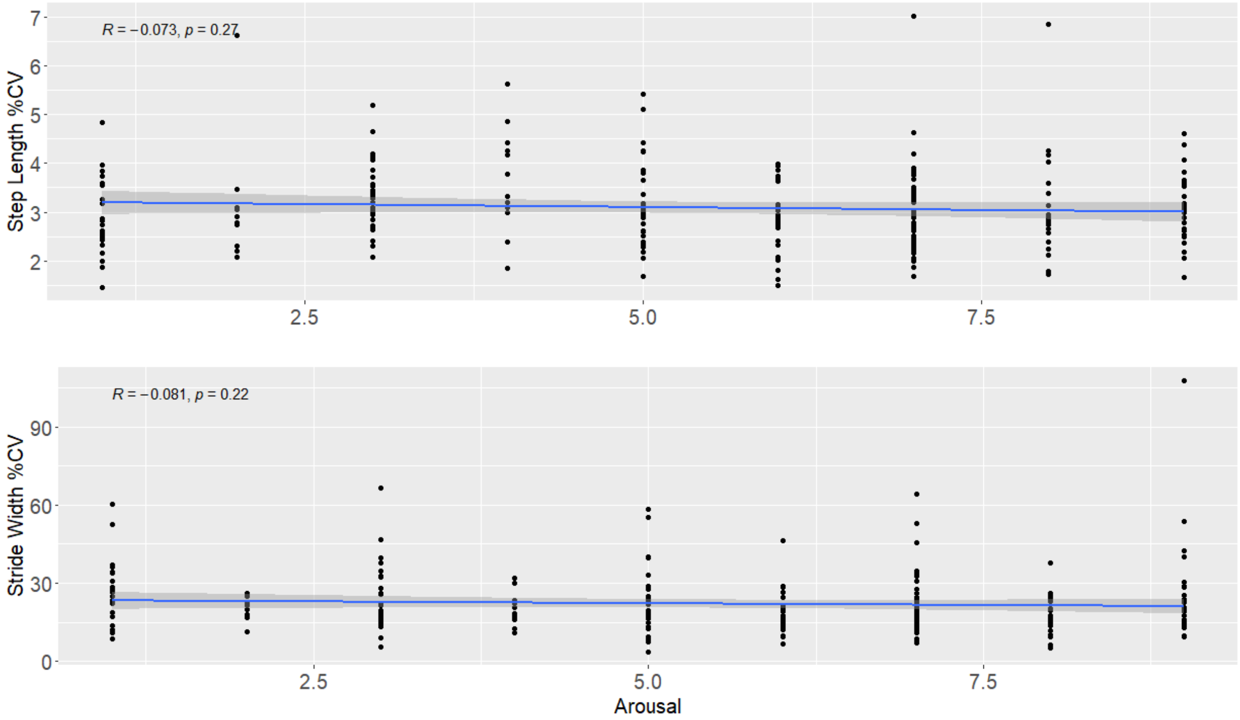


Figure A20: Shows the spearman correlations of the domain of Arousal across the variability domain variables of step length %CV (cm) (top) and stride width %CV (cm) (bottom). R represents spearman's rho.

A21 Spearman Correlation – Arousal & Postural Control

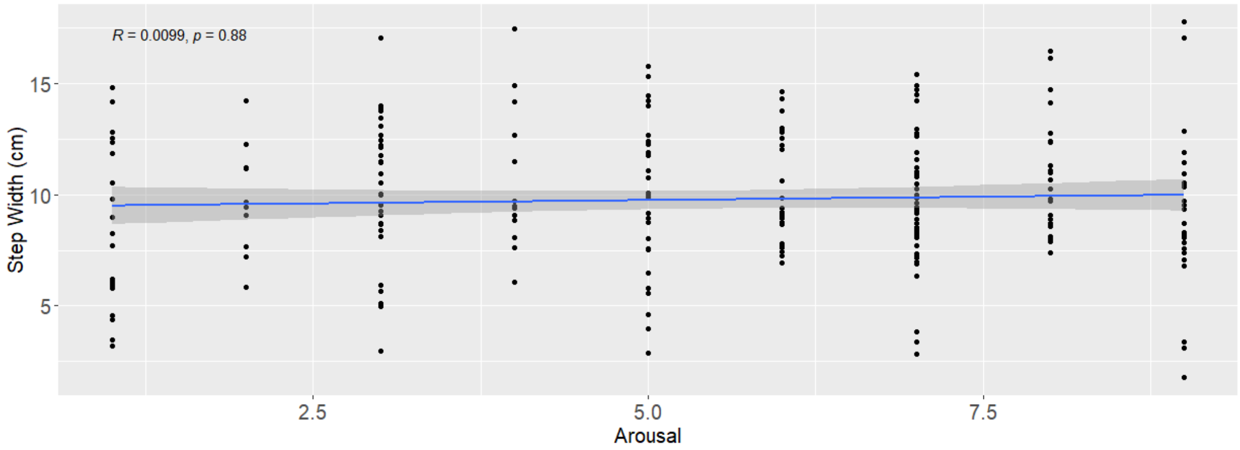


Figure A21: Shows the spearman correlations of the domain of Arousal across the postural control domain variable of step width (cm). R represents spearman's rho.

A22 Spearman Correlation – Dominance & Pace

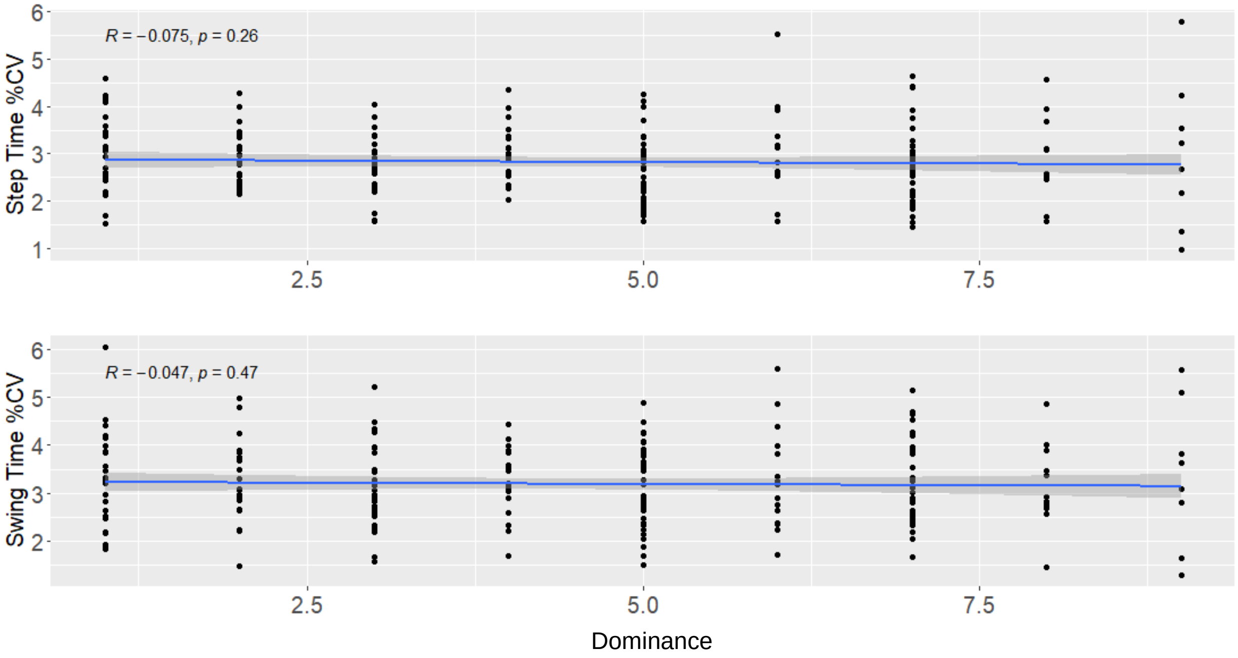


Figure A22: Shows the spearman correlations of the domain of Dominance across the pace domain variables of step time %CV (top) and swing time %CV (bottom). R represents the spearman's rho value.

A23 Spearman Correlation – Dominance & Rhythm

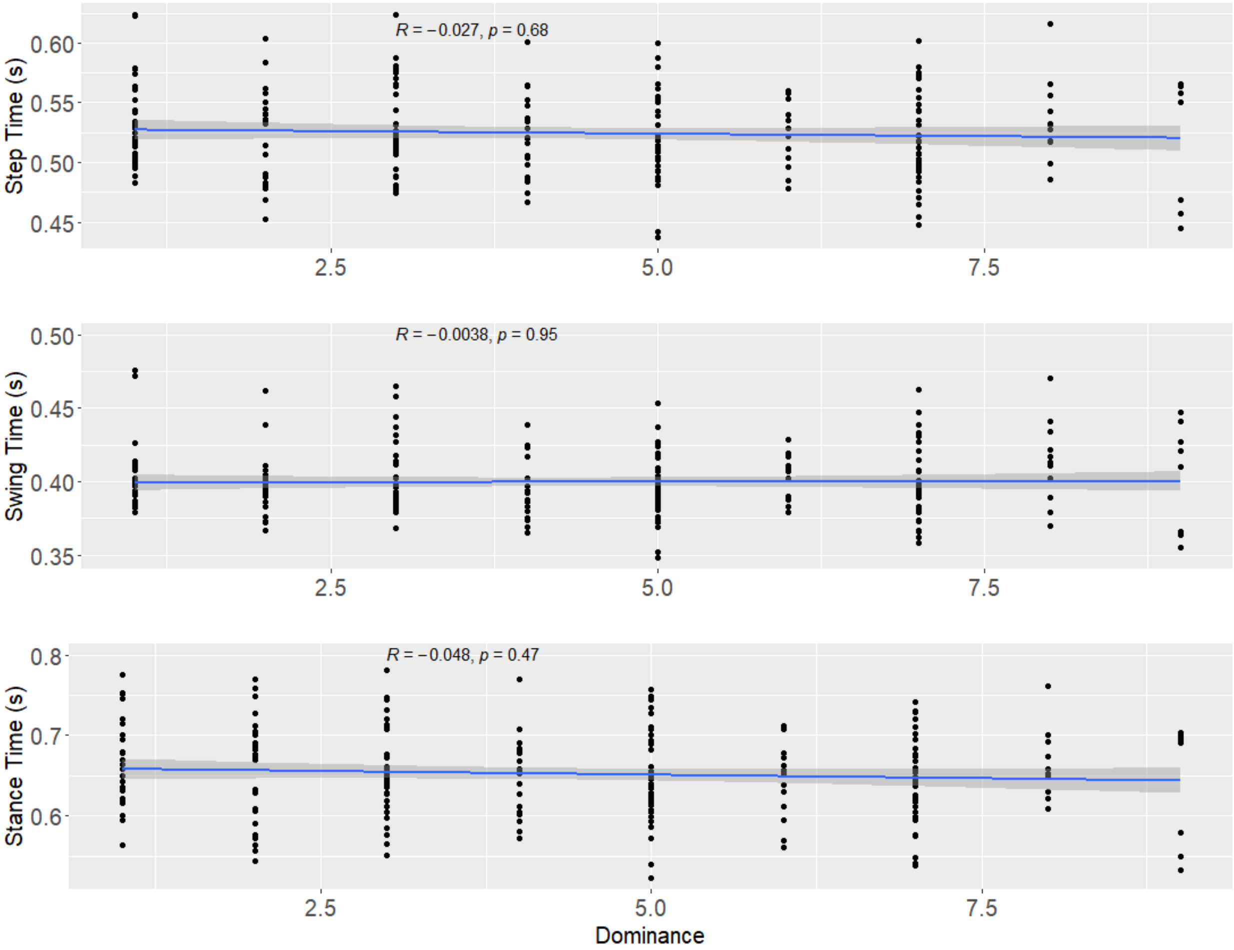


Figure A23: Shows the spearman correlations of the domain of Dominance across the rhythm domain variables of step time (s) (top), swing time (s) (middle) and stance time (s) (bottom). R represents the spearman's rho value.

A24 Spearman Correlation – Dominance & Variability

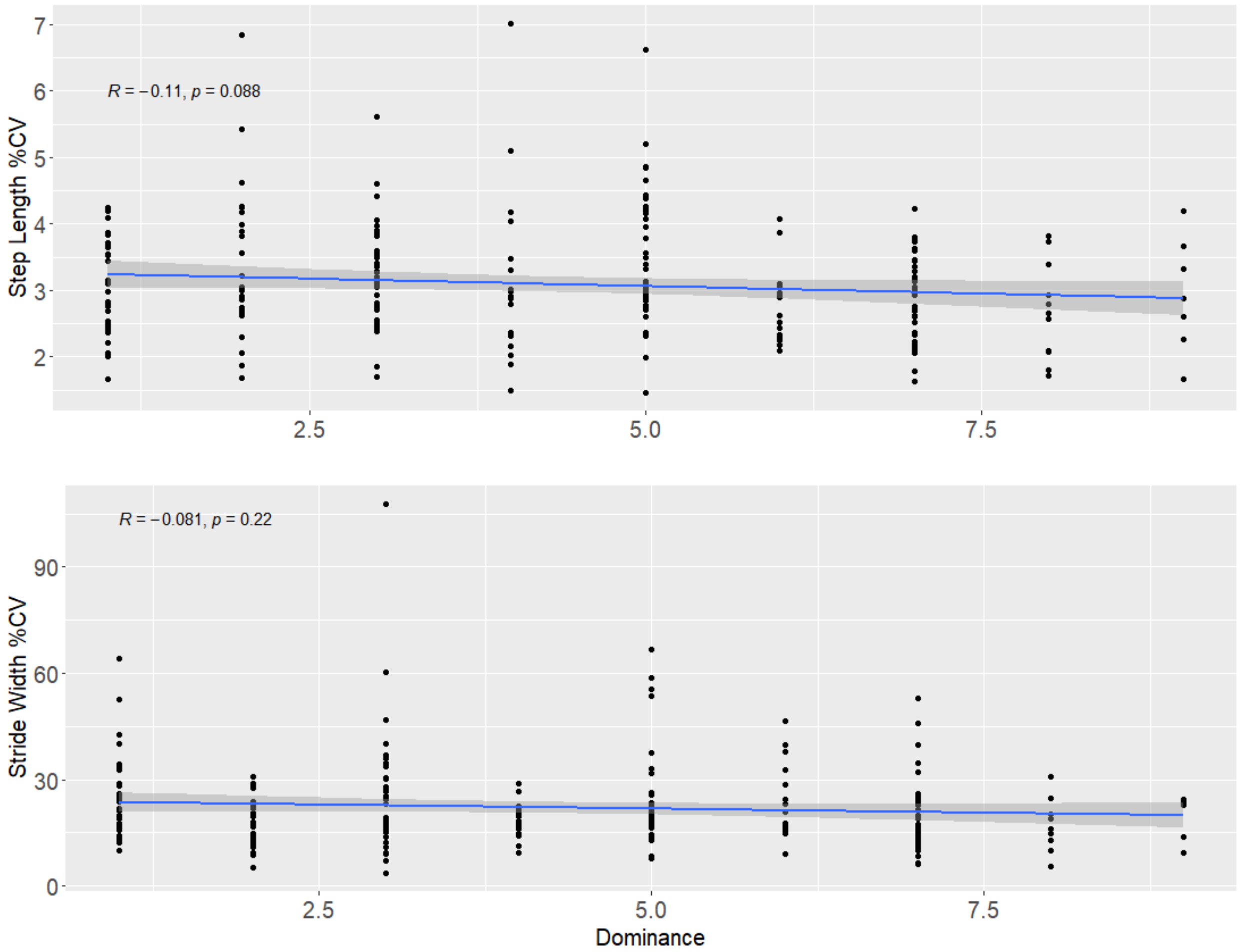


Figure A24: Shows the spearman correlations of the domain of Dominance across the variability domain variables of step length %CV (cm) (top) and stride width %CV (cm) (bottom). R represents spearman's rho.

A25 Spearman Correlation – Dominance & Postural Control

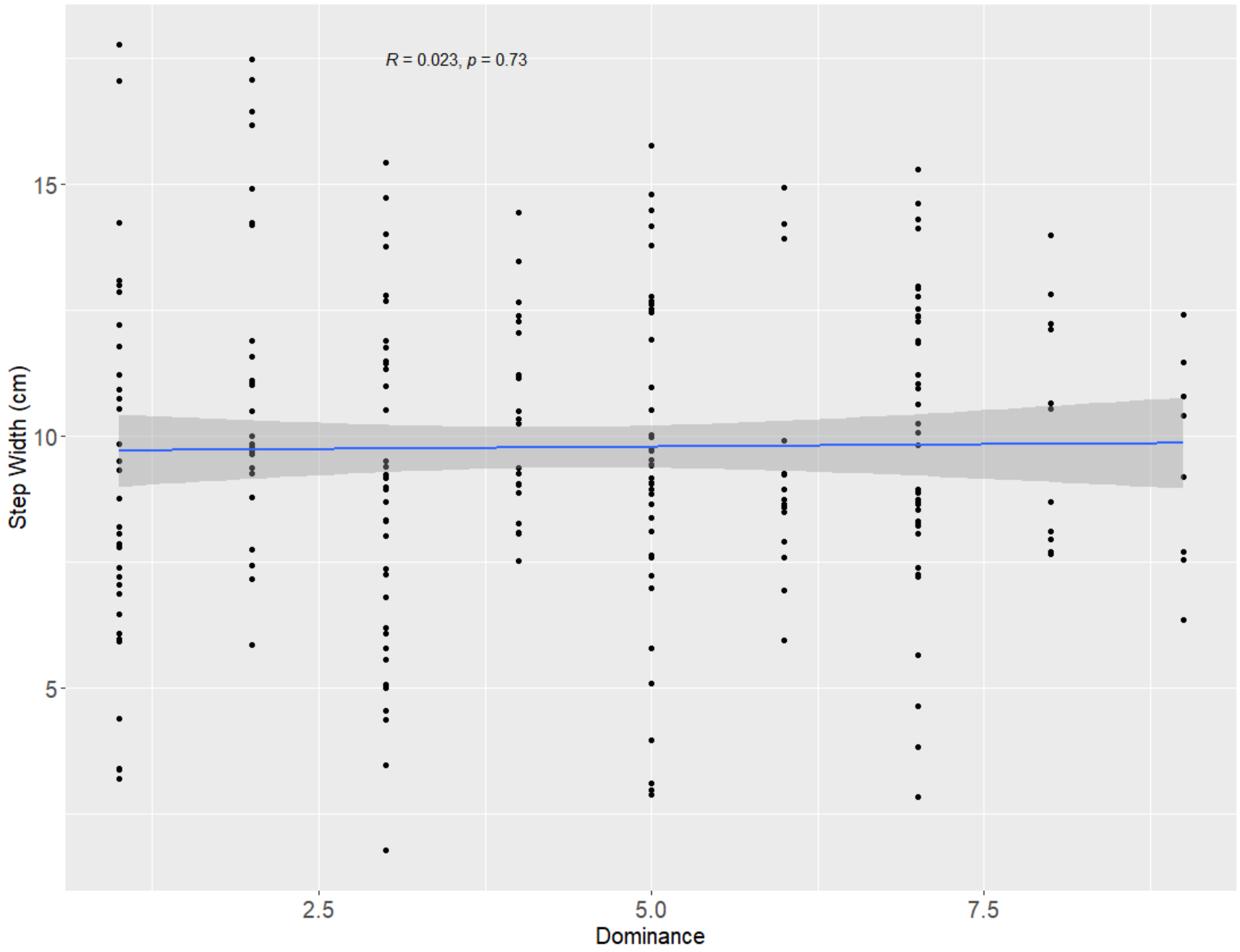


Figure A25: Shows the spearman correlations of the domain of Dominance across the postural control domain variable of step width (cm). R represents spearman's rho.