Effects of Emotion and Mood Phase on Biomechanical Characteristics of Body Movements in Healthy Individuals and Individuals with Bipolar Disorder

By

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DEDICATION

I dedicate my dissertation work to my family.

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PREFACE

The chapters have been written as separate manuscripts for submission, and there may be some repetitions between chapters, specifically in the materials and methods sections. Chapters Two and Three have been published in the *Human Movement Science* and the *Journal of Biomechanics*, respectively.

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ABSTRACT

The effects of emotion on body movement have been quantified using biomechanical analysis in healthy individuals during gait but the generalizability of these findings to other body movements and to individuals with mood disorders is very limited. Current understanding of emotion effects is limited to spatiotemporal and angular measures in gait but it is not known if emotion affects other movements in similar ways, or how emotion might affect coordination of body movement in any movement task.

Assessment of body movements in individuals with mood disorders is a key criterion for diagnosis, but very little data exist on the effect of mood on body movements. Clinical descriptions defining mood phase in bipolar disorder depend on individuals' subjective self-descriptions. A few biomechanical studies of bipolar disorder exist, but they do not report participants' mood phase or they include only one mood phase. Despite the importance of body movement assessment for diagnosis of bipolar disorder, the effects of hypomanic, euthymic and depressed phases on body movements in bipolar disorder have not yet been described quantitatively.

The aim of this dissertation was to investigate the effects of emotion and mood phase on biomechanical characteristics of body movements in healthy individuals and individuals with bipolar disorder. In the first two studies, anger, joy, sadness and neutral emotion were elicited in eighteen healthy individuals while performing sit-to-walk and gait. Movement data were collected using an optoelectronic motion capture system. During sit-to-walk, emotion-related differences were consistent with differences in movement speed so that the shortest durations, greatest

velocities and lowest center-of-mass velocity drops (hesitation) were associated with anger and joy, and the longest durations, lowest velocities and largest hesitation were associated with sadness. In contrast to previous studies based on qualitative observations, movement smoothness, measured as normalized jerk of center-of-mass, was greater for anger or joy than sadness, after accounting for speed effects. During gait, emotion affected spatiotemporal measures in a similar way as sit-to-walk, with movement speed and movement smoothness greater for anger and joy than sadness. These studies demonstrate a consistent effect of emotion on spatiotemporal features and movement smoothness across whole-body tasks, and provide new evidence that emotion affects movement coordination assessed by center-of-mass motion.

In the third study, a biomechanical approach was combined with psychiatric assessment to examine the effects of mood phase on gait in individuals with bipolar disorder. Individuals with bipolar disorder in the hypomanic, euthymic or depressed phase, and healthy controls performed gait at self-selected comfortable, slow and fast speeds. An optoelectronic motion capture system and two force plates were used to collect movement data and ground reaction force data. The hypomanic individuals walked at least 28% faster, with at least 18% greater ground reaction force, and at least 50% greater power generation at the ankle compared with the other individuals, with force and power differences beyond the effect of faster speed. Although 20% of the depressed individuals walked as fast as the hypomanic individuals, the majority of the depressed individuals walked at least 15% slower compared with the other individuals. The euthymic individuals walked at the same speed as healthy controls. Study findings demonstrated that gait speed reflects all mood phases well, and ground reaction force and power generation particularly well-reflects hypomania.

This study suggests that gait speed may be a promising mood-specific biomarker for bipolar disorder.

CHAPTER 1

INTRODUCTION

1.1 Background

Since Darwin first described movement behaviors in people feeling emotions (Darwin, 1872), movements have long been considered as conveying emotion-related information. For example, Darwin noted that joy leads to dancing and jumping, sadness leads to drooping, and anger leads to trembling (Darwin, 1872). More recently, researchers have reported that gesture-like movements emerge while feeling emotions. Wallbott and Scherer (1986) investigated movement behavior in the hand and head while actors engaged in joyful, angry, sad and surprising scripted conversations, and found that sadness was associated with more frequent shrugging movements and more head-down or head-away movements compared with joy, anger and surprise. In another study, Wallbott (1998) examined movement behavior in actors performing scenarios that expressed a variety of emotions. The author found that differences in movement behavior with emotions, such as more frequent stretching of arms in front of the body for cold anger, hot anger, joy and interest than for other emotions, more frequent shoulder-forward movements for disgust, despair and fear than for other emotions, and more frequent crossing of arms in front of the body for pride and disgust than for other emotions. Atkinson et al. (2004) investigated movement

behavior performed with five different emotions, and found that expression of anger included shaking of the fists or stamping of the feet, expression of fear included cowering movements, expression of happiness included raising the arms, expression of sadness included dropping the head, and expression of disgust included bringing one or both hands to the mouth and nose.

Besides affecting which movements are performed, expression of emotion can also affect how a given movement is performed. Montepare et al. (1987) videotaped participants walking while they imagined feeling happiness, sadness, anger, and pride, and then observers identified which emotions were expressed and described the gait characteristics. Observers identified sad gait as having less arm swing, angry gait as being heavyfooted, and proud gait as standing straight up. Crane and Gross (2013) videotaped participants walking while they felt anger, contentment, joy, sadness and neutral emotion, and then observers described gait characteristics using an Effort-Shape analysis in which movement qualities were judged according to torso and limb shape, and four aspects of effort, including space, energy, time and flow. They reported that angry and joyful gait patterns were associated with expanded torso and limb shape and strong and powerful energy, sad gait was associated with contracted torso and limb shape and light and buoyant energy, content gait was associated with expanded torso and limb shape but neither strong nor light energy, and neutral gait was associated with neither contracted nor expanded limb shape, neither indirect nor direct space, and free and relaxed flow. These studies indicate that observers can detect and differentiate the effects of emotion on body movement, but the qualitative nature of the descriptions of emotionally expressive movement patterns are fundamentally limited.

More recently, with the development of 3D motion capture technology, researchers have been able to adopt a quantitative approach to describe the effect of emotion on body movements. Michalak et al. (2009) examined how feelings of happiness and sadness (induced with music)

changed gait patterns. They found that gait speed, vertical movement of the head, and arm swing (i.e., the displacement of the wrist in the anteroposterior direction) decreased by 20.8, 28.5 and 38.0%, respectively, for sadness compared with happiness. Gross et al. (2010) investigated the effects of anger, anxiety, sadness, pride, contentment and joy elicited with an autobiographical recall task on knocking. They found that knocking duration, elbow range of motion and peak elbow flexion angular velocity doubled for anger and joy compared with sadness. The same authors also investigated the effects of anger, sadness, joy, contentment and neutral emotion on kinematics during gait (Gross et al., 2012). They found that gait velocity and stride length increased by approximately 30.0 and 16.0%, respectively, for anger and joy compared with sadness, and the head was approximately 5.0 and 8.0° more flexed for sadness compared with anger and joy, respectively. Fawver et al. (2014) examined how anger, fear, happiness, sadness and neutral emotion elicited with autobiographical recall change kinematic and kinetic characteristics during gait initiation. They reported that step velocity and step length for the first and second steps increased by approximately 0.12 m/s and 0.05 m, respectively, for happiness compared with sadness. They also reported that peak braking and propulsive ground reaction forces for the first step increased by approximately 10 and 20 N, respectively, for both happiness and anger compared with sadness.

The reports by Michalak et al. (2009), Gross et al. (2010 and 2012) and Fawver et al. (2014) demonstrate that feeling emotions affects movement patterns in ways that can be detected and discriminated with kinematic and kinetic analyses. However, the biomechanical studies to date are limited to one whole-body task (walking) and one upper extremity task (knocking). It is not known, for example, if the effects of emotion on body movements are task dependent, or if they can be generalized to other movement tasks. Further, emotion has been defined as a coordinative structure

that creates a "tendency to act" (Frijda, 1987). Thus, it may be that emotion affects coordination of movement tasks, or the overall coordination of the body rather than just affecting the expressive style of the movement. For example, in a complex task like sit-to-walk, it may be that different emotions affect the coordination of the component phases of the task (i.e., sit-to-stand and gait initiation) in different ways. Movement coordination has also been assessed as movement smoothness, or its inverse, movement jerk. Both Montepare et al. (1999) using a qualitative analysis of expressive gestures and Pollick et al. (2001) using a kinematic analysis of emotionally expressive drinking and knocking tasks reported that anger and joy are associated with jerky movement, and sadness is associated with smooth movement. These studies were limited, however, in one study by the qualitative assessment used to assess movement smoothness, and in the other study by the confounding effects of movement time and amplitude on the calculation of jerk (Hogan and Sternad, 2009), so the coordinative effects of emotion on body movement remain to be determined.

Another important aspect of emotion expression in body movement is persistence over time. The difference between emotion and mood has been characterized primarily in terms of time frame (Rottenberg and Gross, 2003; Rottenberg 2005). Rottenberg and Gross (2003) clarified that *emotion* is a coordinated response to meaningful stimuli, and causes overt behavior. In contrast, *mood* is relatively longer, slower moving and less responsive to stimuli compared with emotion. Interestingly, they compared *emotion* to "storms", and *mood* to "seasonal climate change". In a qualitative manner, emotion has been characterized as "more displayed", "intense" and mood has been characterized as "not displayed", "mild" (Parkinson et al., 1996; Beedie et al., 2005). These distinctions between emotion and mood suggest that the effects of mood on movement behavior could be similar to, but may not be in the same as, the effects of emotion on movement behavior.

The impact of mood on whole-body movement has been studied primarily in the context of mood disorders. The major mood disorders -- major depressive disorder and bipolar disorder -- are defined by inappropriate subjective mood states, but the diagnostic criteria also include disturbances in motor behaviors. Lemke et al. (2000) examined spatiotemporal gait parameters such as gait speed and stride length in individuals with major depressive disorder and control individuals with no history of psychiatric disorder. They found that gait speed and stride length were 15.5 and 6.3% less, respectively, for individuals with major depressive disorder compared with control individuals. Michalak et al. (2009) investigated gait patterns in individuals with major depressive disorder and never-depressed control individuals. They reported that individuals with major depressive disorder walked at 17.7% slower speed, with 35.2% less arm swing, and with 5° more slumped head posture compared with control individuals. Hausdorff et al. (2004) reported that individuals with major depressive disorder tended to walk slower compared to healthy individuals, although the difference was not significant. In the case of major depressive disorder, the slower gait speed, reduced movement amplitude and flexed posture are consistent with reports of others for walking with sad emotion (Michalak et al., 2009; Roether et al., 2009; Gross et al., 2012). Importantly, the results of these studies also suggest that whole-body movement behavior may have potential as a clinical marker for mood disorders.

The effect of mood on whole-body movement behavior may provide useful information for bipolar disorder. Bipolar disorder is characterized by unstable mood swings between two extreme mood phases, mania (or hypomania, an attenuated form of mania) and depression, with a relatively normal mood phase, euthymia (American Psychiatric Association, *Diagnostic and Statistical Manual of Mental Disorders*, 2013). Both of the two extreme mood phases are likely to result in devastating consequences in affected individuals' or their families' lives. For example,

risk of financial losses, involvement in illegal activities, or sexual promiscuity increase during mania or hypomania, and risk of suicide increases during depression (American Psychiatric Association, *Diagnostic and Statistical Manual of Mental Disorders*, 2013). However, symptoms of extreme mood phases are based on subjective description rather than objectively measurable biomarkers. Thus, it is necessary to develop validated biomarkers that provide objective information about disease state (i.e., mood phase) or responses to treatment, and are acceptable to patients (Frey et al., 2013). If body movements are mood-specific and change with mood phase, objective measures of mood-related body movements have potential as biomarkers.

Another major problem in bipolar disorder is that moods swing between the extreme mood phases. Proper treatment for an individual with bipolar disorder depends on mood phase. For example, mood stabilizers are recommended for treating an individual during mania or hypomania, and antidepressants are recommended for treating an individual during depression (American Psychiatric Association, *Practice Guideline for the Treatment of Patients with Bipolar Disorder*, 2002). Thus, personalized medicine treating specific mood phases needs to be implemented for an individual with bipolar disorder (Kupfer, 2005; Hamburg and Collins, 2010). However, difficulties in detecting mood swings between extreme mood phases due to lack of mood-specific biomarkers (Frey et al., 2013) have challenged proper personalized treatment for bipolar disorder (Holmes et al., 2016). The development of such biomarkers would help to detect changes in mood, and would eventually allow clinicians to meet the increasing need for personalized medicine.

According to the *Diagnostic and Statistical Manual of Mental Disorders* (5^{th} ed.), abnormal motor behavior associated with each mood phase is critical for a diagnosis of bipolar disorder (American Psychiatric Association, 2013). For example, mania or hypomania is defined as a period experiencing increased activity or energy, and depression is defined as a period experiencing

decreased activity or energy, or being slowed down. Although these behavioral characteristics are core symptoms for bipolar disorder, they are purely based on subjective and qualitative self-reports (Hamilton, 1960; Young et al., 1978; Spitzer et al., 1992; Nurnberger et al., 1994; Altman et al., 1997; Kroenke et al., 2001; Rush et al., 2003), and lack biological validation with objective and quantitative measurement. Since a biomarker needs to provide objective information about mood phase (National Institute of Health Biomarkers Definitions Working Group, 2001; Frye et al., 2015), the abnormal behavioral characteristics cannot be considered as biomarkers for bipolar disorder. Moreover, self-reports from subjective experiences may be biased as evidenced by several studies that reported discrepancies between self-reported and objectively measured cognitive dysfunction in individuals with bipolar disorder (Burdick et al., 2005; Martínez-Arán et al., 2005; Svendsen et al., 2012). Therefore, it is necessary to identify mood-specific abnormal behavior objectively for better characterizing bipolar disorder.

Several studies have used objective measurements of abnormal behavior in individuals with bipolar disorder. Swann et al. (2003) used a laboratory-based neuropsychological test evaluating impulsive responses, and reported that manic bipolar individuals had more impulsive behavior compared to healthy controls. Jones et al. (2005) measured circadian rhythms for seven days using an accelerometer, and reported that euthymic bipolar individuals had more irregular daytime activity compared to healthy controls. Harvey et al. (2008) measured sleep cycles and daytime activity for eight days using an accelerometer, and reported that euthymic bipolar individuals had inefficient sleep (i.e., longer total sleep time and lower daytime activity) compared to individuals with no sleep problems. Objective information reported by these studies helps to better understand the behavioral characteristics of individuals with bipolar disorder. However, the information regarding impulsive behavior and circadian rhythms cannot be collected during a

clinical evaluation because the measurements require a laboratory-based assessment (i.e., impulsive behavior) or a protracted time period for assessment (i.e., circadian rhythms). Therefore, it may be more clinically useful to obtain objective mood-specific behavioral information that can be tested during a clinic visit with simple, quick and patient acceptable behavioral tests.

Ample evidence exists that suggests that gait may be an appropriate motor behavior for assessing mood phase in bipolar disorder, with potential for clinical assessment. According to the National Institute of Mental Health, bipolar disorder affects the ability to perform day-to-day activities (National Institute of Mental Health, 2016), and mood-specific behavioral characteristics may be manifested in an ordinary movement like gait. Gait is affected by other mood disorders, and gait performance differs between individuals with major depressive disorder and healthy controls (Lemke et al., 2002; Michalak et al., 2009). Emotional states also affect gait, and gait performance differs in healthy individuals when they are feeling anger, joy and sadness (Gross et al., 2012; Fawver et al., 2014). Since a number of variables of gait performance such as gait velocity, stride length and force exertion can be objectively quantified, gait variables may serve as mood-specific biomarkers for bipolar disorder. Although differences in gait performance between individuals with bipolar disorder and healthy controls have been reported (Hausdorff et al. 2004), mood phase was not documented so that the feasibility of gait variables as potential mood-specific biomarkers is still unknown.

Although it might be expected that individuals in hypomanic phase would walk more quickly and individuals in depressed phase would walk more slowly, studies have not yet been performed to assess effects of mood phase in bipolar disorder on gait or other ordinary movements. Further, it is not known if the effects of mood phase on body movement are limited to movement speed alone. For example, mood might affect body movements in ways similar to emotion. If so,

depressed mood might be associated with a more flexed posture and jerkier movements, and hypomanic mood with a more extended posture and smoother movements. Since biomechanical assessment of ordinary movement behavior is objective and precise, quantification of movement characteristics in bipolar disorder may lead to development of an accurate and validated mood-specific biomarker.

1.2 Organization of Dissertation

The aim of this dissertation is to investigate the effects of emotion and mood disorders on whole-body movement patterns. The first study (described in Chapter 2) investigates the effects of emotion on the sit-to-walk movement in healthy young adults. The purpose of this study is to advance our understanding of emotional effects on movement behavior by expanding the set of movement tasks in which emotion effects are documented. Specifically, a whole-body movement with subcomponents (sit to stand and gait initiation) will be investigated so that the effects of emotion on movement coordination can be studied. Outcomes of the first study are important to determine whether the effects of emotion on body movement are task specific and if different emotions act to coordinate a complex movement in different ways. The second study (described in Chapter 3) investigates emotional effects on movement smoothness during gait in healthy young adults. The purpose of this study is to expand our knowledge of emotional effects on movement behavior to center of mass motions. Outcomes of the second study are important to determine whether the coordinating effects of emotion on body movement extend to the center of mass rather than just the observable movements of the limbs and body postures. The third study (described in Chapter 4) examines the kinematic and kinetic characteristics of motor behavior in individuals

with BD in hypomanic, euthymic and depressed mood phase and healthy individuals. The purpose of this study is to identify the effects of mood phase on gait characteristics in individuals with BD. Outcomes of the third study are important to determine the biomechanical effects of BD mood phase on gait, and will provide the first kinematic and kinetic analysis of effects of mood phase in BD on body movement. The mood-specific differences in gait characteristics will provide the basis for potential clinical biomarkers and a deeper understanding of the relationship between emotion and mood on movement behavior. Finally, the discussion (provided in Chapter 5) presents the implications of the findings across studies, the strengths and limitation of the dissertation, and suggests a direction for future research.

CHAPTER 2

EMOTIONAL INFLUENCES ON SIT-TO-WALK IN HEALTHY YOUNG ADULTS

The following chapter has been previously published:

Kang, G. E., Gross, M. M., 2015. Emotional influences on sit-to-walk in healthy young adults. Human Movement Science 40: 341-351.

2.1 Abstract

The purpose of this study was to investigate influences of emotional feelings on sit-to-walk. Eighteen healthy young adults performed sit-to-walk while feeling sadness, anger, joy and neutral emotion. Emotions were elicited using an autobiographical memories task. We used an optoelectronic motion capture system to collect motion data and assessed kinematics of sit-to-walk. Emotion-related differences in sit-to-walk kinematics were consistent with differences in movement speed. Compared to neutral emotion, sadness was associated with increased sit-to-walk duration and phase durations, decreased peak forward and vertical center-of-mass velocity, increased drop in forward center-of-mass velocity, and increased forward and vertical normalized jerk score. Anger and joy were associated with decreased sit-to-walk duration and phase durations, increased peak forward and vertical center-of-mass velocity, decreased drop in forward center-of-

mass velocity, and decreased forward and vertical normalized jerk scores compared to neutral emotion. Findings suggest that emotional feelings affect movement speed, hesitation, and movement smoothness during sit-to-walk.

2.2 Introduction

Rising from a chair and walking, referred to as sit-to-walk, is a common and functional movement of daily living. Successful completion of sit-to-walk requires a merging of two component movements, sit-to-stand and gait initiation, with the transition between the component movements occurring near the time of seat-off (Magnan et al., 1996). A high level of balance control is considered a key motor strategy for performing sit-to-walk as the component movements are merged (Magnan et al., 1996). Successful completion of the task requires generation of sufficient vertical momentum to stand up and sufficient horizontal momentum to initiate gait while maintaining balance during the transition. The maintenance of horizontal momentum between the standing up and gait initiation phases has been used as a measure of the effective transition between the tasks, typically assessed as the relative decrease in forward velocity of the center-of-mass between standing up and walking.

Previous studies have shown that the ability to effectively coordinate the component movements in sit-to-walk is negatively affected by age, neurological disorder, and risk of falling. Sit-to-walk duration and duration of component phases were greater for healthy older adults compared to healthy young adults (Buckley et al., 2009), and for older adults with Parkinson's disease (Buckley et al., 2008), stroke (Dion et al., 2003; Frykberg et al., 2009), risk of falling (Kerr et al., 2007) and history of falling (Chen and Chou, 2013; Chen et al., 2013). In the gait initiation phase, initial step length and velocity were less for healthy older adults compared to healthy young

adults (Buckley et al., 2009), and for older adults with Parkinson's disease (Buckley et al., 2008), and a history of falling (Chen and Chou, 2013; Chen et al., 2013). The ability to maintain horizontal velocity during sit-to-walk, measured as drop in forward velocity, was decreased in healthy older adults compared to older adults with risk of falling (Kerr et al., 2013). It is likely that a combination of diminished strength and age-related or disorder-related change in motor control explains the observed changes in sit-to-walk performance.

Another factor that has been shown to affect the whole-body movements like sit-to-walk is emotion. During gait initiation, when healthy young adults were exposed to high and low arousing pleasant stimuli, the velocity of the first step and the displacement of the center of pressure increased with high compared to low arousing unpleasant stimuli (Naugle et al., 2011). Also, in healthy young adults, exposure to unpleasant stimuli increased time to peak center-of-mass velocity compared to exposure to pleasant stimuli while the peak center-of-mass velocity remained similar for both stimuli (Gélat et al., 2011). Sad walking in healthy young adults has been characterized by decreased walking speed, reduced range of limb motion, and increased postural flexion of the neck and thorax, and joyful walking has been associated with increased walking speed, large joint ranges of motion, and greater trunk extension and shoulder girdle depression postural angles (Michalak et al., 2009; Gross et al., 2012). How emotion might affect performance of standing up, the initial component of the sit-to-walk task, or the transition between sit-to-walk component movements is not yet known.

According to an integrative approach proposed by Russell (1980), an emotion can be described by its location in a two-dimensional space, with emotional valence and emotional arousal comprising the two independent dimensions. In the circumplex model, location on the valence axis represents the degree of pleasantness or unpleasantness for an emotion, and location

on the arousal axis represents the degree of excitement or calm for an emotion (Posner et al., 2005). According to this model, sadness is a combination of low arousal and unpleasant valence, anger is a combination of high arousal and unpleasant valence, and joy is a combination of high arousal and pleasant valence. Neutral emotion represents the midpoint on emotional valence and arousal axes.

In this study, we investigated the effect of emotion on sit-to-walk performance in healthy young adults. We expected that emotion would affect sit-to-walk by altering movement speed, and that the resulting speed-related changes in sit-to-walk performance would be similar to those reported by others. Specifically, we hypothesized that high arousal emotions would increase movement speed, and low arousal emotions would decrease movement speed, as others have observed during gait. Because velocity is important in the transition between the standing up and gait initiation phases of sit-to-walk, we also hypothesized that emotion-related changes in movement speed would affect coordination between these component phases of the task.

To test our hypotheses, we asked participants to perform sit-to-walk while experiencing four target emotions - sadness, anger, joy and neutral emotion. By comparing sit-to-walk performed while experiencing high arousal emotions with opposite valences (i.e., anger and joy), we could examine the effects of emotional valence on sit-to-walk independent of arousal. Similarly, by comparing sit-to-walk performed while experiencing unpleasant emotions with different levels of arousal (i.e., anger and sadness), we could examine the effects of emotional arousal on sit-to-walk independent of valence. How emotional valence and arousal might affect sit-to-walk, and how emotion might affect the transition between component movements in a whole-body task like sit-to-walk, are novel questions posed in this study.

2.3 Methods

2.3.1 Participants

Eighteen healthy young adults (11 women and 7 men) recruited from the university community participated in this study. Mean age and height were 20.2 years (SD: 1.8 years) and 1.67 m (SD: 0.07 m), respectively. Participants had no musculoskeletal or neurological conditions that might affect sit-to-walk. Each participant gave written informed consent approved by University of Michigan Institutional Review Board before beginning the experiment and was paid for their participation.

2.3.2 Emotion manipulation

After signing informed consent, we used an autobiographical memories paradigm to induce the four target emotions of anger, sadness, joy and neutral emotion (Gross et al., 2010; Gross et al., 2012). Each participant was asked to write down life events from their past in which each of the target emotions was felt. Texts used in recalling angry, sad, joyful and neutral events were "Think of a time in your life when you: (1) felt very offended, when you felt furious or enraged, or felt like you wanted to explode"; (2) "felt in despair, when you felt low or depressed, or felt like you wanted to withdraw from the world"; (3) "felt exhilarated, when you felt euphoric or very playful, or felt like you wanted to jump up and down"; and (4) "did not feel any emotion, for instance, when you put gas in your car or did your laundry", respectively. Participants spent as much time as they needed for recalling their life events.

2.3.3 Experimental procedures

After participants completed the writing task, participants changed into tight-fitting exercise clothes without shoes, and we attached forty-one markers on the following bony landmarks: bilateral markers on the first metatarsal head, lateral malleolus, calcaneus, shank, lateral epicondyle of the femur, greater trochanter, anterior superior iliac spine, posterior superior iliac spine, acromion, upper arm, lateral epicondyle of the humerus, forearm, ulnar styloid process, radial styloid process, the second metacarpal head, forehead and posterior head, and single markers on suprasternal notch, xiphoid process, C7, T10 and the right scapula. Then, we asked participants to warm up by performing a series of activities like walking across the laboratory comfortably and fast, swinging arms, smiling, frowning, and looking around the laboratory. Participants were encouraged to perform the activities until they felt comfortable in the laboratory circumstance.

We used an eight-camera motion capture system (Motion Analysis, Santa Rosa, CA, USA) that surrounded a 10-m walkway. We placed a backless and armless stool (0.52 m) in the middle of the walkway. Motion data were sampled at 60 Hz and filtered at 6 Hz using a 4^{th}-order Butterworth low-pass filter.

Prior to recalling each target emotion, participants read the life events that they had written down to help recall their past memories and feelings. For each sit-to-walk trial, we encouraged participants verbally by saying “be in the memory”, “remember the feeling strongly”, and “stand up and walk across the room when the feeling is strong” while they were sitting on the stool. Participants initiated movement and selected their own movement speed. Between target emotions, participants performed an emotionally neutral task (i.e., card sorting) to wash out the emotion they

had felt in the previous sit-to-walk trial. Three sit-to-walk trials were performed with each target emotion in a block, and the order of target emotion blocks was randomized.

After each sit-to-walk trial, participants rated the intensity that they felt the four target emotions while they were performing sit-to-walk using a 5-item Likert scale (0 = not at all; 1 = a little bit; 2 = moderately; 3 = quite a bit; 4 = extremely) to rate the intensity. Trials with at least moderate intensity for anger, sadness and joy were coded as felt for angry, sad and joyful trials, respectively. Trials with neutral emotion were coded as felt if participants felt neutral emotion with at least moderate intensity, and felt angry, sad and joyful emotions with less than moderate intensity.

2.3.4 Data analysis

The whole-body center-of-mass was computed from a 15-segment biomechanical model using Visual 3D (C-Motion, Germantown, MD, USA). We calculated the duration of each of the four component phases of sit-to-walk (Kerr et al., 2004). The four phases of sit-to-walk were identified from five events using the whole-body center-of-mass and foot markers. Specifically, the first event, onset of sit-to-walk, was defined as the instant when initial movement of the whole-body center-of-mass occurred in the forward direction. Since a force plate was not used in this study, the second event, seat-off, was defined as the instant of the first local minimum of the vertical velocity of the whole-body center-of-mass. The third event was defined as the instant of peak vertical velocity of the whole-body center-of-mass. The fourth event, swing leg toe-off, was defined as the onset of vertical motion from a toe marker on leading foot. The fifth event, stance leg toe-off, was defined as the onset of the vertical motion from a toe marker on trailing foot. Sit-

to-walk total duration was calculated as the interval between the first and fifth events. Phases 1, 2, 3 and 4 were calculated as the interval between the first and second events, the second and third events, the third and fourth events, and the fourth and fifth events, respectively.

We calculated center-of-mass position, velocity, acceleration and jerk in forward, vertical and lateral directions for each sit-to-walk trial (Fig. 2.1). We calculated velocity drop as the difference between initial positive and subsequent negative peaks of the forward center-of-mass velocity, and then calculated the ratio of velocity drop as the difference with respect to the initial peak forward center-of-mass velocity (Fig. 2.1). We calculated the normalized jerk score in forward, vertical and lateral directions as jerk ($\dddot{x}(t)$, the third time derivative of center-of-mass position) normalized to sit-to-walk duration (T) and center-of-mass displacement (D) in the corresponding direction $\left(\sqrt{\frac{1}{2}\cdot\frac{T^5}{D^2}\cdot\int \dddot{x}(t)^2 dt}, \text{unitless}\right)$ (Ketcham et al., 2002; Caligiuri et al., 2006). Finally, center-of-mass lateral displacement was defined as the difference between maxima of the right and left center-of-mass positions during sit-to-walk.

Only trials in which the target emotion was felt were included in the analysis. All of the outcome variables were averaged across the sit-to-walk trials for each felt-target emotion for each participant. We used the averaged values for each participant for each target emotion in the statistical analysis.

2.3.5 Statistical analysis

We used a mixed model with random effects of participants and fixed effects of emotion and gender to evaluate effects on outcome variables. Post hoc analysis with Bonferroni correction was used to compare significant differences between emotions ($p < 0.05$). We calculated effect

size as Cohen's *d*. We considered $d < 0.2$ as a small effect, $0.2 \leq d < 0.5$ as a medium effect and $0.5 \leq d < 0.8$ as a large effect.

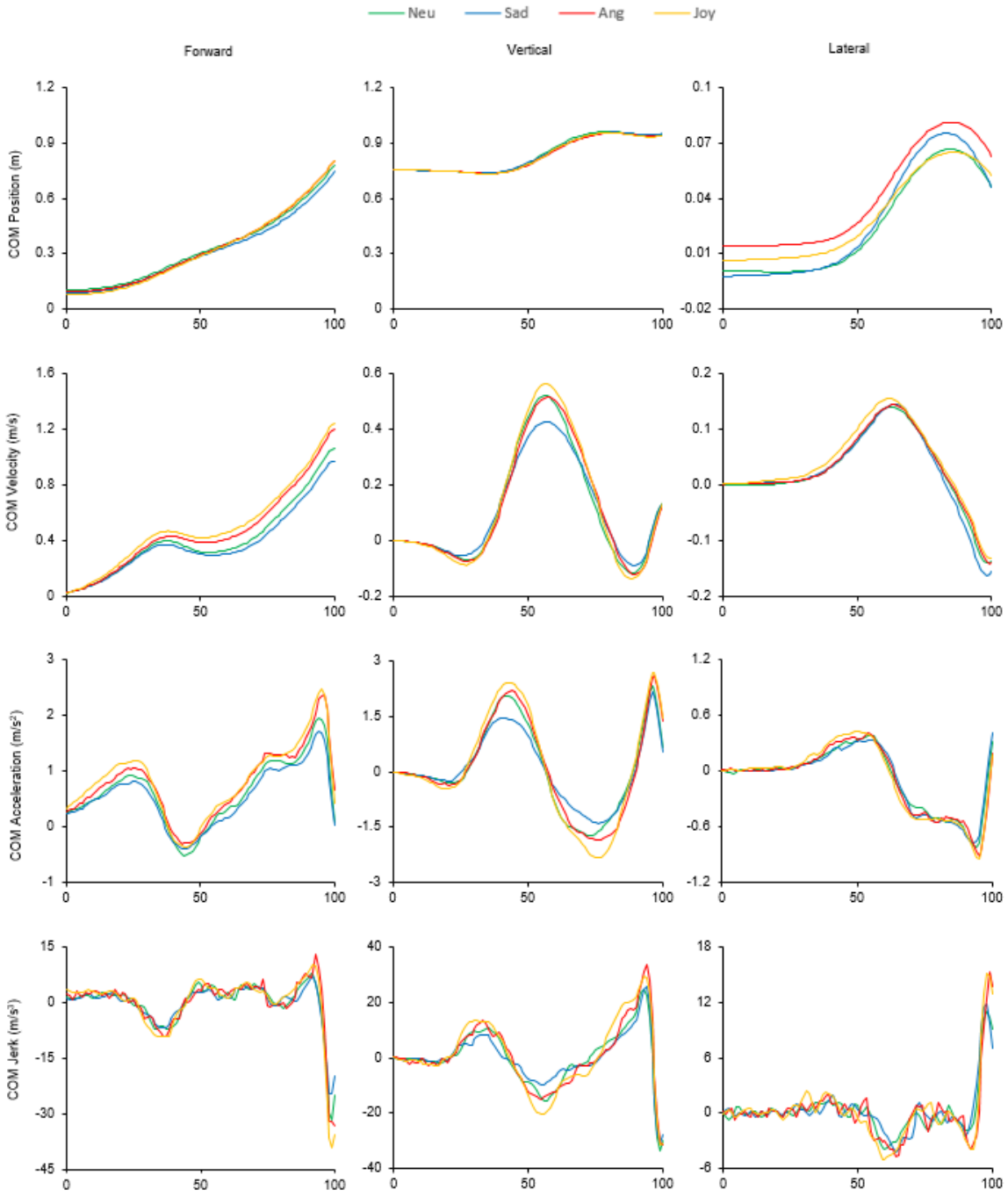

Fig. 2.1. Mean center-of-mass (COM) position (first row), velocity (second row), acceleration (third row) and jerk (fourth row) in forward (left column), vertical (middle column) and lateral (right column) directions across participants for each target emotion normalized to percent of sit-to-walk (STW) duration. For lateral direction, positive sign means the direction contralateral to the initial swing leg.

2.4 Results

2.4.1 Trial selection and mood intensity

We collected 216 trials (18 participants × 4 target emotions × 3 repetitions). Among 216 trials, we excluded 18 trials due to marker occlusion (14 trials: five neutral, three angry, two sad and four joyful trials), not-felt target emotions (three neutral trials), and protocol violation (one sad trial). As a result, 198 trials (46 neutral, 51 angry, 51 sad and 50 joyful trials) were included in the data analysis.

Mean mood intensities for each target emotion for sit-to-walk trials were greater than 3 ("quite a bit") (Table 2.1). For neutral trials, mean mood intensity was 3.6 for neutral emotion and less than 1 for the other target emotions. For sad trials, mean mood intensity was 3.1 for sadness and less than 1 for the other target emotions. For angry trials, mean mood intensity was 3.3 for anger, 1.1 for sadness and less than 0.5 for neutral emotion and joy. For joyful trials, mean mood intensity was 3.5 for joy and less than 0.5 for the other target emotions.

Table 2.1
Mean mood intensities for sit-to-walk trials across participants.

	Mood intensity			
Target emotions	Neutral	Sad	Angry	Joyful
Neutral	3.6 (0.1)	0.2 (0.1)	0.1 (0.1)	0.1 (0.0)
Sad	0.6 (0.3)	3.1 (0.3)	1.1 (0.3)	0.0 (0.0)
Angry	0.1 (0.0)	0.7 (0.2)	3.3 (0.2)	0.0 (0.0)
Joyful	0.1 (0.0)	0.0 (0.0)	0.0 (0.0)	3.5 (0.1)

Note: Values in parentheses are standard errors.

2.4.2 Movement duration

2.4.2.1 Sit-to-walk duration

Sit-to-walk duration differed among the target emotions ($p < 0.001$). Sit-to-walk duration was shorter for joy (15.4%) than for neutral emotion ($p = 0.001$, $d = 1.08$) (Table 2.2). Sit-to-walk duration was also shorter for anger (14.1%) and for joy (19.0%) than for sadness (both $p < 0.001$) ($d = 1.05$ and 1.40, respectively). Sit-to-walk duration was not affected by gender.

Table 2.2
Mean sit-to-walk durations (s), drop in forward center-of-mass (COM) velocities (m/s), the ratios of velocity drop to initial peak in forward COM velocity (no unit) and lateral COM displacements (cm) in sit-to-walk trials with each target emotion across participants.

	Neutral	Sad	Angry	Joyful
Sit-to-walk duration	1.72 (0.05)^{J**}	1.84 (0.07)^{A***J***}	1.58 (0.05)^{S***}	1.49 (0.05)^{N**S***}
Velocity drop	0.12 (0.01)	0.14 (0.01)^{J**}	0.10 (0.01)	0.10 (0.01)^{S**}
Velocity drop ratio	0.29 (0.03)^{J*}	0.34 (0.04)^{A**J***}	0.22 (0.03)^{S**}	0.19 (0.03)^{N*S***}
COM displacement	8.1 (0.8)	8.5 (0.9)	7.7 (0.8)	8.1 (2.1)

Note: Values in parentheses are standard errors. Superscript letters refer to significant differences between target emotions: N=Neutral, S=Sad, A=Angry, J=Joyful. $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

2.4.2.2 Phase duration

When considered as a percentage of total sit-to-walk duration, the relative durations for phase 1, 2, 3 and 4 (29, 27, 12 and 31%, respectively) were similar among the target emotions (all $p > 0.05$). Absolute phase durations, however, differed among the target emotions (all $p < 0.05$) (Fig. 2.2). The duration of phase 1 increased 16.3% for neutral emotion and 18.9% for sadness

compared to joy (both $p < 0.01$) ($d = 0.74$ and 0.93, respectively). The duration of phase 1 also tended to decrease for anger compared to sadness (11.3%, $p = 0.051$, $d = 0.59$). The duration of phase 2 decreased 11.8% for neutral emotion, 15.7% for anger and 17.6% for joy compared to sadness (all $p < 0.02$) ($d = 0.71$, 0.91 and 1.19, respectively). The duration of phase 4 decreased 12.8% for joy compared to neutral emotion ($p = 0.023$, $d = 0.86$), and decreased 12.5% for anger and 16.1% for joy compared to sadness (both $p < 0.05$) ($d = 0.69$ and 0.96, respectively). The duration of phase 3 tended to be less for anger and joy than for sadness and neutral emotion, but the differences were not significant. None of the phase durations were affected by gender.

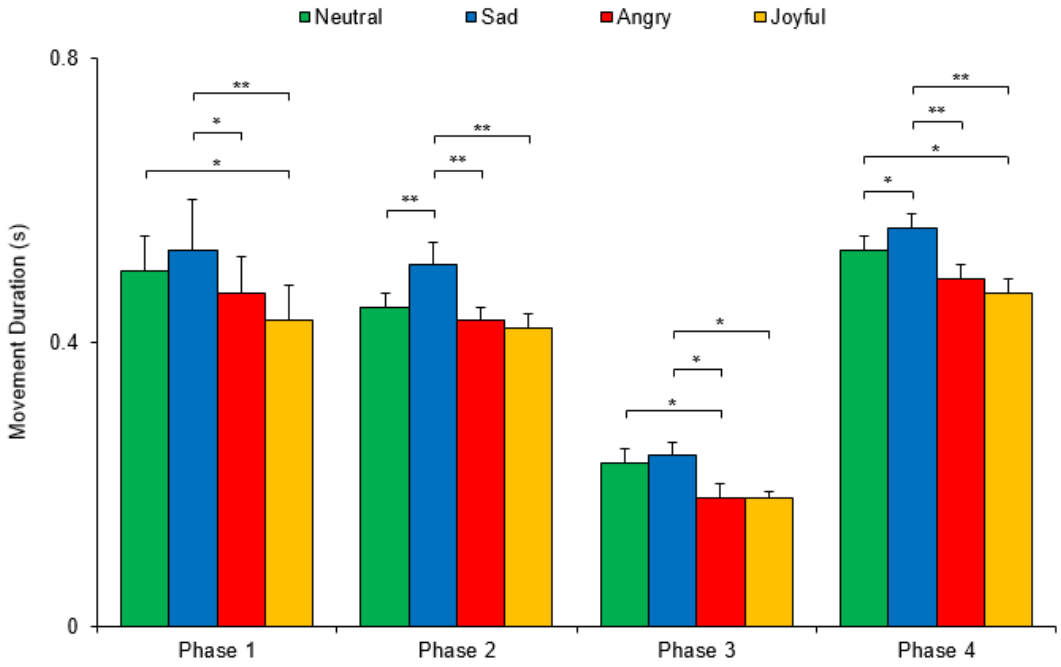

Fig. 2.2. Mean durations for sit-to-walk phases for each target emotion across participants. The error bars represent standard error of the mean. Asterisks indicate significant differences between target emotions. * $p < .05$. ** $p < .01$.

2.4.3 Center-of-mass velocity

2.4.3.1 Peak center-of-mass velocity

Emotion affected peak center-of-mass velocity in the forward and vertical directions ($p < 0.001$), but not the lateral direction (Fig. 2.3). Peak forward center-of-mass velocity increased 10.8% for anger and 13.7% for joy compared to neutral emotion (both $p < 0.01$) ($d = 0.78$ and 1.10, respectively). Peak forward center-of-mass velocity increased 23.7% for anger and 27.8% for joy compared to sadness (both $p < 0.001$) ($d = 1.26$ and 1.57, respectively). Peak vertical center-of-mass velocity increased 14.3% for neutral emotion, 16.3% for anger and 22.4% for joy compared to sadness (all $p < 0.01$) ($d = 0.76$, 0.91 and 1.29, respectively).

Gender affected peak vertical and lateral center-of-mass velocities, but not peak forward center-of-mass velocity. Peak vertical center-of-mass velocity was 0.08 m/s greater in men than women ($p = 0.033$, $d = 0.84$). Peak lateral center-of-mass velocity was 0.07 m/s greater for men than for women ($p = 0.005$, $d = 1.46$).

2.4.3.2 Drop in forward center-of-mass velocity

Velocity drop and the ratio of velocity drop differed among the target emotions (both $p < 0.05$) (Table 2.2). The drop in forward center-of-mass velocity decreased 28.6% for joy compared to sadness ($p = 0.005$, $d = 0.72$). The ratio of velocity drop to initial peak in forward center-of-mass velocity decreased 35.3% for anger and 44.1% for joy compared to sadness (both $p < 0.01$) ($d = 0.82$ and 1.06, respectively). The ratio of velocity drop to initial peak in forward center-of-

mass velocity decreased 52.6% for joy compared to neutral emotion ($p = 0.011$, $d = 0.79$). Velocity drop and the ratio of velocity drop were not different for men and women.

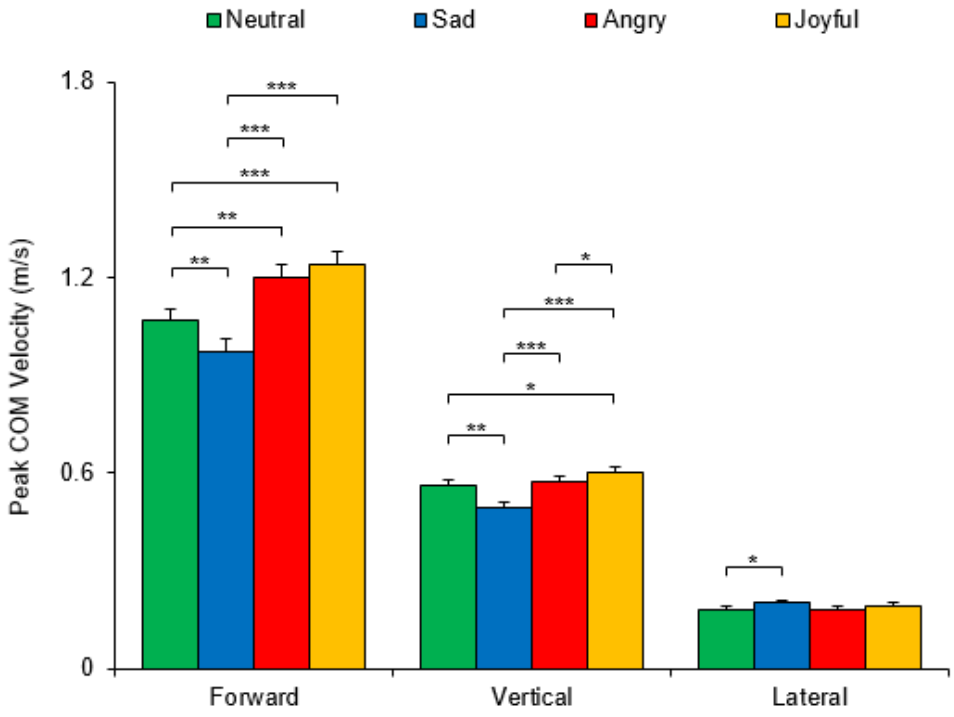

Fig. 2.3. Mean peak center-of-mass (COM) velocities in forward, vertical and lateral directions during sit-to-walk for each target emotion across participants. The error bars represent standard error of the mean. Asterisks indicate significant differences between target emotions.
* $p < .05$. ** $p < .01$. *** $p < .001$.

2.4.4 Normalized jerk score

Normalized jerk score differed among the target emotions in the forward and vertical directions (both $p < 0.001$), but not in the lateral direction (Fig. 2.4). In the forward direction, normalized jerk score decreased 37.1% for joy compared to neutral emotion ($p = 0.028$, $d = 0.90$). Forward normalized jerk score decreased 26.9% for anger and 40.0% for joy compared to sadness (both $p < 0.01$) ($d = 0.71$ and 1.21, respectively). Normalized jerk score in the vertical direction decreased 23.9% for joy compared to neutral emotion ($p = 0.033$, $d = 0.69$). Vertical normalized

jerk score decreased 20.7% for anger and 27.4% for joy compared to sadness (both $p < 0.05$) (d = 0.78 and 0.99, respectively). Gender did not affect normalized jerk score in the forward and vertical directions but lateral normalized jerk score was 907 greater for women than for men ($p = 0.021$, d = 0.98).

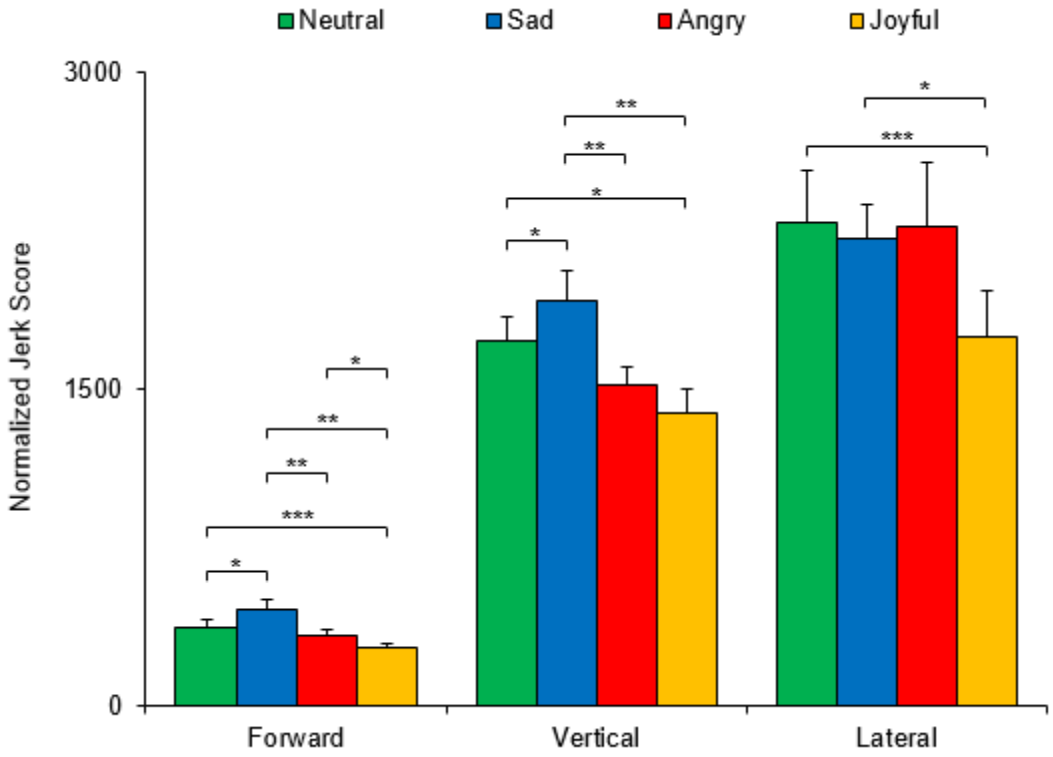

Fig. 2.4. Mean normalized jerk score for the center-of-mass in forward, vertical and lateral directions during sit-to-walk for each target emotion across participants. The error bars represent standard error of the mean. Asterisks indicate significant differences between target emotions. * $p < .05$. ** $p < .01$. *** p < *.001.*

2.4.5 Lateral center-of-mass displacement

Lateral center-of-mass displacement did not differ among the target emotions (Table 2.2). Lateral center-of-mass displacement was 5.1 cm greater in men than women ($p < 0.001$, $d = 2.17$).

2.5 Discussion

In this study, we investigated the influence of feeling different emotions on sit-to-walk in healthy young adults. The key finding of this study was that sit-to-walk kinematics changed when feeling different emotions in ways that were consistent with changes due to differences in movement speed. We found that sit-to-walk was performed similarly when feeling emotions with similar movement speeds regardless of valence (i.e., anger and joy), further supporting the finding that movement speed dominated the effect of emotion on center-of-mass kinematics during sit-to-walk. We also found differences in sit-to-walk performance between men and women, particularly as related to lateral movements of the center-of-mass. This study extends the findings of previous studies by expanding the scope of movement tasks with demonstrated emotional effects to include sit-to-walk. To our knowledge, this is the first study to demonstrate the effect of emotion on the transition between tasks in a whole-body movement.

We anticipated that the low arousal emotion of sadness would slow down sit-to-walk and the high arousal emotions of anger and joy would speed up sit-to-walk. Recent studies have shown that sad walking is associated with slower walking speeds, and angry and joyful walking are associated with faster walking speeds (Michalak et al., 2009; Roether et al., 2009; Gross et al., 2012), and that the velocity of the first step during gait initiation was decreased for low arousal, unpleasant stimuli compared to high arousal pleasant stimuli (Naugle et al., 2011). As expected, we found that sit-to-walk duration decreased with joy, and tended to increase with sadness and decrease with anger, compared to neutral emotion. Sit-to-walk duration for neutral emotion reported in this study (1.72 s) was greater than sit-to-walk durations reported in previous studies for young adults (1.5 s; Kerr et al., 2007; Buckley et al., 2009). Since our participants were asked

to recall a situation in which they felt neutral emotion, the increased sit-to-walk duration may reflect the effect of a cognitive demand during movement, consistent with the increased movement duration observed when young adults perform cognitive tasks when walking (Yogev-Seligman et al., 2013).

The effect of emotion on phase durations during sit-to-walk showed similar patterns to the total sit-to-walk duration. The durations of phase 1, 2 and 4 were greater for sadness than for anger and for joy. In phase 1 (i.e., between onset of sit-to-walk and seat-off), the trunk rapidly flexes, and in phase 2, (i.e., between seat-off and peak vertical center-of-mass velocity), the trunk and lower limbs extend, generating the horizontal and vertical momentum needed to complete sit-to-walk (Kerr et al., 2004). Since slower sit-to-walk movements have been associated with lower horizontal and vertical momentum (Buckley et al., 2009), the increased durations of phase 1 and 2 (and accompanying lower horizontal and vertical velocities) for sadness compared to anger and joy are consistent with the lower momenta for slower sit-to-walk movements observed by others. The duration of phase 3 tended to decrease for anger and joy, and increase for sadness compared to neutral emotion but the differences were not significant. Any changes in phase 3 duration were likely not as consequential as changes in durations of the other phases because duration of phase 3 was less than half of the other phases. Since the relative duration of each phase was not affected by the target emotions, the underlying coordination of the task was not disrupted by feeling the different emotions.

Overall, peak forward and vertical center-of-mass velocities varied with sit-to-walk movement duration and phase durations. Peak forward center-of-mass velocity occurred at the end of phase 4 (i.e., between swing leg toe-off and stance leg toe-off) as walking commenced, and was significantly less for sadness than for anger and for joy. Peak vertical center-of-mass velocity

occurred in phase 2, as trunk and lower limbs extended to bring the body to upright, and was significantly less for sadness than for the other emotions. The peak vertical center-of-mass velocity was similar between joy and anger, suggesting that any valence-related differences in emotional experience did not affect center-of-mass velocity. Previous studies have reported differences in trunk angle when individuals walked at similar speeds while feeling anger and joy (Gross et al., 2012). It is possible that trunk posture differed during sit-to-walk when individuals felt anger and joy in this study even though the center-of-mass velocities were similar between high arousal emotions.

We examined the ratio of velocity drop to initial peak in forward center-of-mass velocity to evaluate the transition between sit-to-walk component movements, with a smaller drop indicating better maintenance of forward momentum and a more effective transition between the component tasks of standing up and initiating gait (Kerr et al., 2013). The ratio of velocity drop has also been defined as "hesitation" during sit-to-walk, with a smaller drop indicating a more fluid motor strategy (Dion et al., 2003; Kerr et al., 2013). We found that the transition was most effective for the high arousal emotions (anger and joy). The velocity drop ratio was similar for neutral emotion and sadness (29 and 34%, respectively), and was similar to a value reported for healthy young adults (30.3%) (Kerr et al., 2013). The velocity drop ratio that we observed for sit-to-walk for anger and joy, however, was significantly less than for sadness. Since the drop in forward center-of-mass velocity is related to a reduction in forward momentum, the decreased forward momentum in slower sit-to-walk movements may not be sufficient to transfer to vertical momentum, resulting in greater "hesitation" and less fluidity than in faster sit-to-walk movements, regardless of emotion when performing the task.

We used normalized jerk score to demonstrate the effect of emotions on movement smoothness during sit-to-walk, with smaller normalized jerk score indicating smoother movements. We found that sit-to-walk smoothness was least when feeling sad, as evidenced by significantly greater normalized jerk score in both horizontal and vertical directions. Sit-to-walk movement duration was increased with sadness, and it may be that the speed of the movement itself increased the normalized jerk score. Others have reported a relationship between normalized jerk score and movement duration, showing that normalized jerk score and the number of secondary submovements increased with movement duration during aiming movements (Ketcham et al., 2002). Although we did not document submovements during sit-to-walk, additional submovements may have occurred with adjustments of the trunk and lower limbs to preserve balance during the slow sit-to-walk, increasing the normalized jerk score and decreasing movement smoothness.

The smoothest sit-to-walk movements tended to occur when feeling joy in all three directions. Normalized jerk score in the forward and vertical directions were significantly lower than neutral for joy but not for anger. These observations suggest that feeling joy resulted in a slightly different movement pattern, independent of movement speed, which tended to increase the smoothness of sit-to-walk when feeling joy.

In general, we found that movement speed and emotional arousal were related, but movement smoothness tended to be greater for joy than anger even though the sit-to-walk movements had similar movement durations. This observation is consistent with a study of arm movements in which a strong relationship was observed between wrist kinematics and participants' categorizations of emotions in a psychological space that was analogous to the arousal and pleasantness axes of the circumplex model (Pollick et al., 2001). In that study, increased

movement velocity and jerk were associated with increased arousal but decreased pleasantness. Observers tended to categorize wrist movements with higher velocities as belonging to higher arousal emotions (e.g., happiness and anger), but wrist movements with more jerk as belonging to less pleasant emotions (e.g., sadness and anger). Thus, our observation that anger tended to have more jerk than joy is consistent with a separation among high arousal emotions along a pleasantness continuum, and supports the notion that movement smoothness may be a feature of emotion embodiment.

We found that some aspects of sit-to-walk performance differed between men and women, particularly in the lateral direction. Peak lateral center-of-mass velocity, lateral center-of-mass displacement and lateral normalized jerk score, and peak vertical center-of-mass velocity, were different in men than in women. Assuming that taller individuals have a greater vertical excursion of the center-of-mass during sit-to-walk, the greater mean body height of men in our study (9.5 cm, $p < 0.01$) may explain the difference in peak vertical velocity of the center-of-mass. The increased displacement and velocity of the center-of-mass in the lateral direction, and decreased lateral normalized jerk score in men, however, may reflect differences in gendered movement styles between men and women. Others have reported increased lateral movement at the shoulders in men compared to women during walking (Murray et al., 1970; Gross et al., 2012) and greater lateral displacement of the shoulders has been judged as a more masculine gait style ("swagger") (Johnson et al., 2007). Thus, the increased lateral displacement of the shoulders in men may have been due to increased body height, increased willingness to allow more lateral displacement, or both. The increased lateral center-of-mass velocity may explain the increased smoothness of movement (i.e., smaller normalized jerk score) across emotions in men. This finding suggests that gender should be included in future investigations of sit-to-walk performance.

2.6 Conclusion

In conclusion, feeling emotions was associated with changes in kinematics during sit-to-walk. The effect of emotion on sit-to-walk was similar to the effect of emotion on other whole-body movements, that is, movement speed increased with arousal for both pleasant and unpleasant emotions. Our findings demonstrated that, compared to sadness, sit-to-walk duration, phase durations, drop in forward center-of-mass velocity, and forward and vertical normalized jerk score decreased significantly, and peak forward and vertical center-of-mass velocity increased significantly when anger and joy were felt. To our knowledge, this is the first study to examine emotional influences on kinematics of sit-to-walk, a complex whole-body movement that requires coordinated merging of component tasks. This study is also to the first to use kinematic measures to quantify the effect of emotion on smoothness of a whole-body movement. We observed a tendency for movement smoothness to increase with pleasant emotion during sit-to-walk, suggesting that movement smoothness should be investigated in future studies of emotion embodiment.

CHAPTER 3

THE EFFECT OF EMOTION ON MOVEMENT SMOOTHNESS DURING GAIT IN HEALTHY YOUNG ADULTS

The following chapter has been previously published:

Kang, G. E., Gross, M. M., 2016. The effect of emotion on movement smoothness during gait in healthy young adults. Journal of Biomechanics 49: 4022-4027.

3.1 Abstract

This study aimed to investigate the effect of emotion on movement smoothness during gait. We followed an autobiographical memories paradigm to induce four target emotions, neutral emotion, sadness, anger and joy, in eighteen healthy young adults. Participants performed gait trials while feeling the target emotions. We collected gait data using an eight-camera optoelectronic motion capture system. We measured spatiotemporal gait parameters, smoothness of linear movements for the whole-body center-of-mass, head, thorax and pelvis in the anteroposterior, vertical and mediolateral directions, and smoothness of angular movements in the sagittal plane for the shoulder, elbow, wrist, hip, knee and ankle. Movement smoothness was measured as jerk, the first time derivative to acceleration, normalized to movement distance and stride time. Compared to sadness, gait speed increased with anger and joy, and spatiotemporal

parameters associated with increased gait speed changed accordingly. In the vertical direction, movement smoothness in the whole-body center-of-mass, head, thorax and pelvis increased for anger and joy compared to sadness. In the anteroposterior direction, movement smoothness increased only for the head for neutral emotion, anger and joy compared to sadness. In the mediolateral direction, emotion did not affect movement smoothness. In angular movements, smoothness in the hip and ankle increased for anger compared to sadness. Smoothness in the shoulder increased for anger and joy compared to sadness. The present findings suggest that emotion affects movement smoothness during gait, and that anger and joy are associated with increased movement smoothness.

3.2 Introduction

Feeling emotions influences gait patterns. Montepare et al. (1987) characterized gait performed with sadness, anger, happiness and pride based on observations. They reported that emotional gait can be qualitatively described like “heavyfootedness” for angry gait. Crane and Gross (2013) applied a systematic analysis based on observations of movement qualities to gait performed with neutral emotion, anger, contentment, joy and sadness. They reported the movement qualities were distinct for gait performed with different emotions. These studies suggest that emotion affects body movements in ways that can be detected by observers, but the qualitative descriptors limit biomechanical quantification of the effects.

Researchers have quantified body movements during emotional gait. Michalak et al. (2009) investigated gait characteristics associated with sadness and happiness. They found, compared to happiness, decreased gait speed, arm swing and vertical movement, and increased body sway and

slumped posture for sadness. Roether et al. (2009) examined important features for perceiving anger, happiness, sadness, fear and neutral emotion from gait. They identified that speed and posture are critical for emotion perception during gait. Gross et al. (2012) investigated how gait changes while feeling neutral emotion, anger, contentment, joy and sadness. They reported the fastest gait speeds for anger and joy, the slowest gait speeds for sadness, and corresponding changes in limb movements to changes in gait speeds. They reported, however, that postural changes in the upper body are independent of gait speed. These studies document attributes of body movement during emotional gait, but it is difficult to relate biomechanical findings to the observational descriptors provided in the existing literature. The effect of emotion may be to coordinate body movement, as suggested by Frijda (1987), defining emotion as a "tendency to act". Thus, biomechanical variables that assess movement coordination may be useful in documenting the effect of emotion on body movement.

Smoothness is considered as a measure of coordinated movement (Hogan and Sternad, 2009) but it has been investigated in only a few movement studies of emotion. Montepare et al. (1999) documented qualitative smoothness during expressive gestures for neutral emotion, happiness, anger and sadness. They reported "jerky movement" for happiness and anger, and "smooth movement" for neutral emotion and sadness. Pollick et al. (2001) measured jerk, the first time derivative to acceleration, of the wrist during drinking and knocking performed with strong, happy, excited, angry, neutral, relaxed, afraid, sad, tired and weak affects. They reported jerkier movement for angry, excited, happy, strong and neutral affects compared to sad, tired, relaxed, weak and afraid affects. In contrast, Kang and Gross (2015) measured normalized jerk of the whole-body center-of-mass during sit-to-walk performed with neutral emotion, sadness, anger and joy. They found the opposite result, that is, jerkier movement for sadness than for anger and joy.

One possible reason for these conflicting findings may be how smoothness was assessed. If movement time and amplitude are not normalized, jerk increases with faster and larger movements (Hogan and Sternad, 2009). Findings from Montepare et al. (1999) were based on observers' qualitative judgements, and it is unclear which particular aspects of body movement were assessed or what the influence of movement time and amplitude might have been on the observers' judgements. Jerk reported by Pollick et al. (2001) was not normalized thus could be confounded by movement time and amplitude (Hogan and Sternad, 2009). To control for the potential confounding effects of movement speed, it may be necessary to quantify movement smoothness using normalized jerk measures.

Another possible reason for these conflicting findings may be related to the notion of emotion acting to coordinate body movements (Frijda, 1987). It is possible that the expressive demands on the body might be different for individual body segments and the whole-body center-of-mass. If this is the case, it may be that emotion coordinates motions of all segments of the body to achieve an expressive goal, regardless of the consequences on motion of the whole-body center-of-mass. By investigating normalized jerk in body segments and the center-of-mass, we may understand better how emotion coordinates body movements.

An emotion can be described using a combination of emotional arousal and valence, based on the circumplex model (Russell, 1980). The emotional arousal and valence indicate the degrees of activation-deactivation and pleasantness-unpleasantness, respectively. For example, sadness is an emotion with low arousal and unpleasant valence (Posner et al., 2005). Emotions with different arousals and valences can be elicited in the laboratory by recalling past episodes of one's own life, referred to as "autobiographical memory". Retrieval of an autobiographical memory includes several neural processes associated with brain activities in the prefrontal cortex (Svoboda et al.,

2006; Cabeza and St Jacques, 2007). Briefly, an autobiographical memory requires efforts that search one's memory about an event, infer the event and detect errors about the event, and finally one constructs the autobiographical memory. These neural processes entail an emotion (Svoboda et al., 2006; Cabeza and St Jacques, 2007), which are manifested in emotionally expressive movements.

We aim to investigate the effect of autobiographically recalled emotions on movement smoothness during gait in healthy young adults. We quantified jerk normalized to movement time and amplitude for measuring smoothness. Comparing anger and sadness enabled us to examine how emotional arousal independent of valence affects smoothness. We were also able to examine how emotional valence independent of arousal affects smoothness by comparing joy and anger. Finally, we explored associations between movement coordination during gait and emotions based on these comparisons.

3.3 Methods

3.3.1 Participants

Eighteen adults with no musculoskeletal or neurological illnesses participated in this study (11 women; age = 20.2 ± 1.8 years; height = 1.67 ± 0.07 m). Informed consent approved by the University of Michigan Institutional Review Board was obtained from all participants.

3.3.2 Procedures

We used an eight-camera motion capture system (Motion Analysis, Santa Rosa, CA, USA) to collect motion data from 41 reflective markers attached on participants' anatomical landmarks: bilaterally on the anterior superior iliac spine, posterior superior iliac spine, greater trochanter, lateral epicondyle of the femur, shank, lateral malleolus, heel, the first metatarsal head, acromion, upper arm, lateral epicondyle of the humerus, forearm, ulnar styloid process, radial styloid process, the second metacarpal head, forehead and posterior head, and unilaterally on the suprasternal notch, xiphoid process, C7, T10 and right scapula. We sampled motion data at 60 Hz, and filtered the data at 6 Hz using a 4^{th}-order Butterworth low-pass filter.

Participants performed sit-to-walk and gait along a 10-m walkway while feeling four target emotions, neutral emotion, anger, sadness and joy. Sit-to-walk results have been reported elsewhere (Kang and Gross, 2015). Three gait trials with each target emotion were performed in a block, and the target emotion blocks were in randomized order across participants. For eliciting the target emotions, we followed an autobiographical memories paradigm that has been used in previous work (Roether et al., 2009; Gross et al., 2010; Gross et al., 2012; Barliya et al., 2013; Fawver et al., 2014). Participants wrote a note about their own life events that met criteria for the four target emotions. The criteria were "you felt very offended, when you felt furious or enraged, or felt like you wanted to explode" for anger, "you felt in despair when you felt low or depressed, or felt like you wanted to withdraw from the world" for sadness, "you felt exhilarated when you felt euphoric or very playful, or felt like you wanted to jump up and down" for joy, and "you did not feel any emotion, for instance, when you put gas in your car or did your laundry" for neutral emotion. Just before each target emotion block, participants read the notes that they had written

down. For each trial in a target emotion block, participants spent as much time as needed to recall the life event for the target emotion. Between each target emotion block, participants spent approximately 5 minutes on card sorting task for washing out the previous target emotion.

After each trial, the intensity with which the target emotion was felt was assessed using a 5-item Likert scale (0 = not at all; 1 = a little bit; 2 = moderately; 3 = quite a bit; 4 = extremely) (Table 3.1). For angry, sad and joyful trials, we included trials if the intensity of the target emotion was greater than 1 ("a little bit"). For neutral trials, we included trials if the intensity of neutral emotion was greater than 1 ("a little bit"), and the intensity of the other target emotions was less than 2 ("moderately").

Table 3.1
Mean values for mood intensities in gait trials with each target emotion across participants.

	Mood intensity			
Target emotions	Neutral	Sad	Angry	Joyful
Neutral	3.5	0.2	0.2	0.2
Sad	0.2	3.3	1.2	0.0
Angry	0.2	0.7	3.2	0.0
Joyful	0.2	0.0	0.0	3.6

3.3.3 Data analysis

We used Visual 3D (C-Motion, Germantown, MD, USA) for biomechanical analysis. We created a 15-segment biomechanical human model: head, thorax, upper arms, forearms, hands, pelvis, thighs, shanks, and feet. Data analysis was performed for one gait cycle from each gait trial. We followed a kinematic method to identify gait cycles (Zeni, Jr. et al., 2008).

We calculated spatiotemporal gait parameters (Table 3.2). For assessing movement smoothness in the whole-body center-of-mass, head center-of-mass, thorax center-of-mass and pelvis center-of-mass, we calculated linear jerk (J, m/s^3) in the anteroposterior, vertical and mediolateral directions (Fig. 3.1). For assessing movement smoothness in the upper and lower limbs, we calculated angular jerk (J, deg/s^3) in the sagittal plane for the hip, knee, ankle, shoulder, elbow and wrist (Fig. 3.2). Then, we calculated normalized jerk scores as suggested by Hogan and Sternad (2009) (Eq. 1), accounting for stride time (T) and movement distance (D). Lower normalized jerk score indicated greater movement smoothness.

$$\text{Normalized jerk score} = \sqrt{\frac{1}{2} \cdot \frac{T^5}{D^2} \cdot \int J^2 dt} \text{ (dimensionless)} \quad \text{(Eq. 1)}$$

For each participant, we calculated mean values for the outcome variables across gait trials for each target emotion. We calculated mean values for each target emotion across participants. For statistical analysis, we used a mixed model with random effects of participants and fixed effects of target emotions and gender. We performed post-hoc pairwise analyses with Bonferroni correction to compare significant differences in the outcome variables between target emotions ($p < 0.05$).

Table 3.2

Mean values for spatiotemporal gait parameters in gait trials with each target emotion across participants.

Parameters	Neutral	Sad	Angry	Joyful
Gait speed (m/s)	1.24 (0.03) ^{A***J***}	1.18 (0.05) ^{A***J***}	1.41 (0.05) ^{N***S***}	1.41 (0.04) ^{N***S***}
Stride length (m)	1.32 (0.03) ^{A***J***}	1.28 (0.03) ^{A***J***}	1.41 (0.04) ^{N***S***}	1.42 (0.03) ^{N***S***}
Cadence (strides/min)	56.7 (0.8) ^{A**J**}	55.2 (1.1) ^{A***J***}	59.5 (1.1) ^{N**S***}	59.2 (0.1) ^{N**S***}
Stride time (s)	1.06 (0.01) ^{A**J*}	1.10 (0.02) ^{A***J***}	1.02 (0.02) ^{N**S***}	1.02 (0.02) ^{N*S***}
Double limb support (%)	28.0 (0.6) ^{A***J***}	28.4 (0.6) ^{A***J***}	26.5 (0.6) ^{N***S***}	26.4 (0.5) ^{N***S***}

Note: Values in parentheses mean standard errors. Superscript letters are significant differences between target emotions based on pairwise comparisons: A=Angry, J=Joyful, N=Neutral, S=Sad. * $p < .05$. ** $p < .01$. *** $p < .001$.

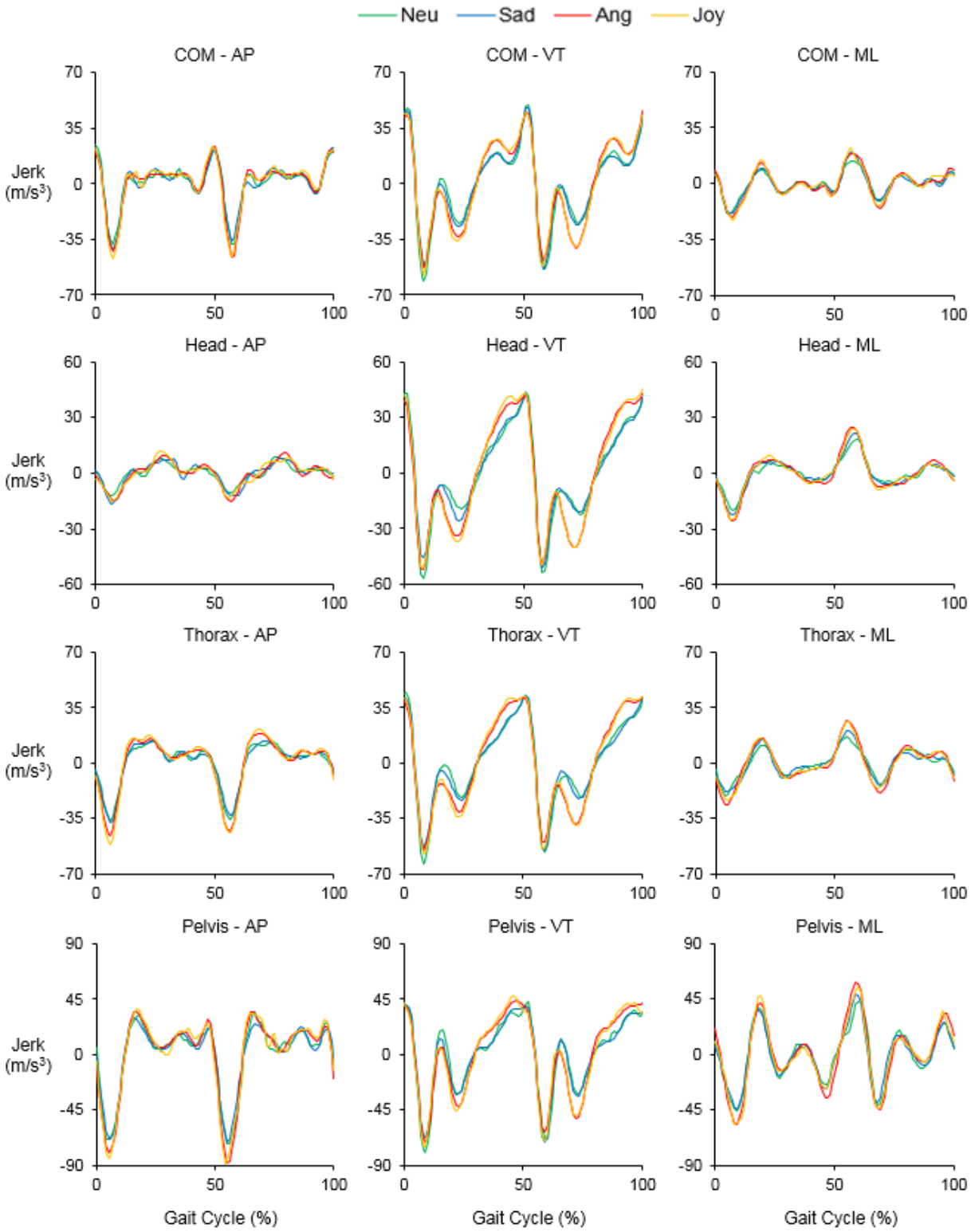

Fig. 3.1. Mean linear jerk for the whole-body center-of-mass (COM), head, thorax and pelvis in the anteroposterior (AP), vertical (VT) and mediolateral (ML) directions across participants for each target emotion during one gait cycle. Positive values in the AP, VT and ML directions indicate forward direction, upward direction, and ipsilateral direction to the stance leg, respectively.

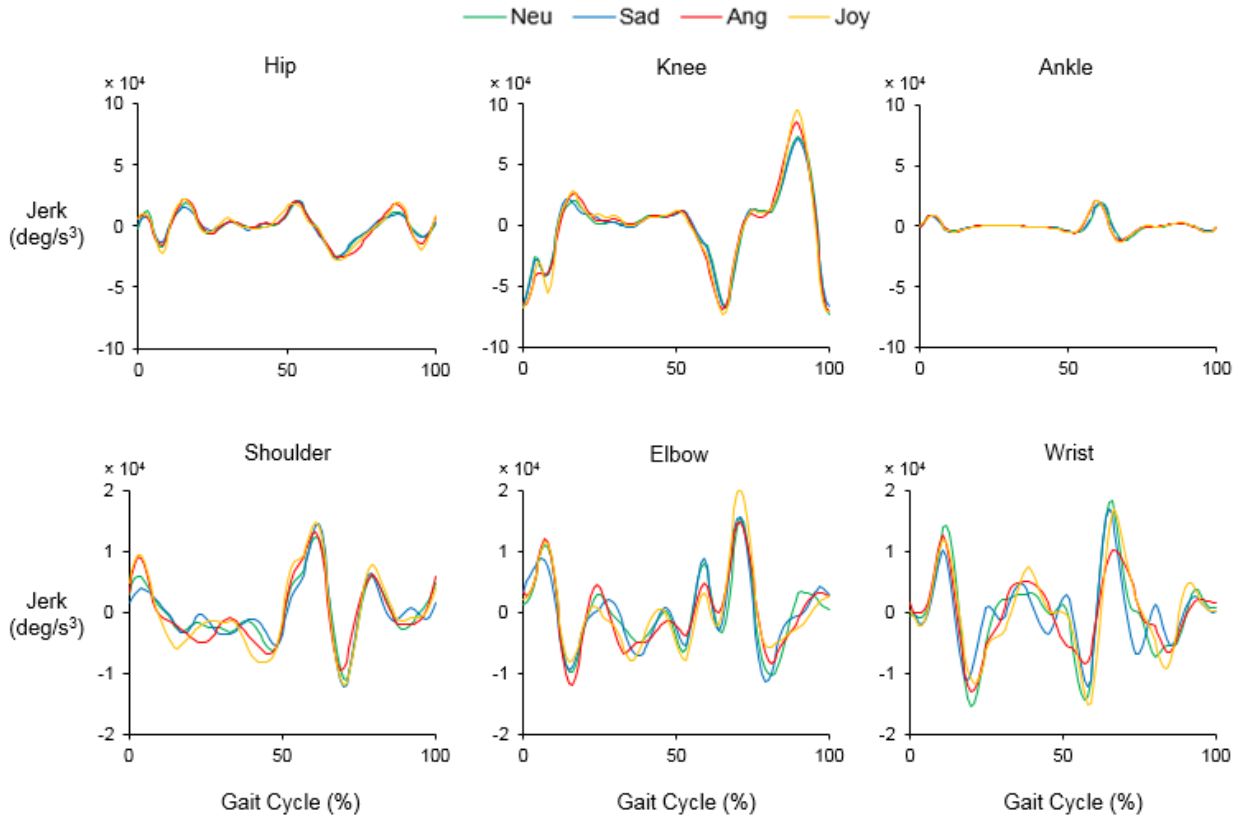

Fig. 3.2. Mean angular jerk in the sagittal plane for the hip, knee, ankle, shoulder, elbow and wrist across participants for each target emotion during one gait cycle. Positive values indicate flexion for the hip, knee, shoulder, elbow and wrist, and dorsiflexion for the ankle.

3.4 Results

A total of 216 gait trials (54 trials × 4 target emotions) were collected. Among them, 3 neutral, 1 angry and 1 joyful trials were excluded because intensities for the target emotions were less than 2 ("moderately"). Thus, we analyzed 211 gait trials (51 neutral, 53 angry, 54 sad and 53 joyful trials). Mean intensities for each target emotion were greater than 3 ("quite a bit") (Table 3.1).

Spatiotemporal gait parameters differed among the target emotions ($p < 0.001$). Gait speed, stride length and cadence were greater for anger and joy than for neutral emotion and sadness (all

$p < 0.01$) (Table 3.2). Stride time and the percentage of double limb support were greater for neutral emotion and sadness than for anger and joy (all $p < 0.05$) (Table 3.2). Gait speed, stride length and the percentage of double limb support were not affected by gender. Cadence and stride time differed between men (55.0 strides/min and 1.10 s, respectively) and women (59.3 strides/min and 1.02 s, respectively) (both $p < 0.05$).

In the vertical direction, normalized jerk score for the whole-body center-of-mass, head, thorax and pelvis differed among the target emotions (all $p < 0.01$). Vertical normalized jerk score were greater for sadness than for anger and joy in the whole-body center-of-mass, head, thorax and pelvis (all $p < 0.05$) (Table 3.3). In the anteroposterior direction, normalized jerk score for the head differed among the target emotions ($p < 0.01$). Anterior-posterior normalized jerk score were greater for sadness than for neutral emotion, anger and joy in the head (all $p < 0.05$) (Table 3.3). Vertical normalized jerk score and anteroposterior normalized jerk score were not affected by gender. In the mediolateral direction, normalized jerk score for the whole-body center-of-mass, head, thorax and pelvis did not differ among the target emotions (all $p > 0.05$) (Table 3.3). Between men and women, mediolateral normalized jerk score were similar for the whole-body center-of-mass and pelvis but were greater for women in the head (1227 and 1537, respectively) and thorax (1434 and 2062, respectively) (both $p < 0.05$).

Normalized jerk score differed for the hip, ankle and shoulder among the target emotions ($p < 0.05$). Normalized jerk score were greater for sadness than for anger in the hip, ankle and shoulder ($p < 0.05$) (Table 3.4). Normalized jerk score for the shoulder were greater for sadness than for joy ($p < 0.01$) (Table 3.4). Normalized jerk score were not affected by gender for the hip, knee and ankle but normalized jerk score for the shoulder, elbow and wrist were greater in men

(3436, 38794 and 30966, respectively) than in women (2380, 8836 and 14835, respectively) (all $p < 0.05$).

3.5 Discussion

We investigated the effect of emotion on movement smoothness during gait. The target emotions affected linear movement smoothness in the whole-body center-of-mass, head, thorax and pelvis, and angular movement smoothness in the hip, ankle, and shoulder. Anger and joy were associated with increased movement smoothness compared to neutral emotion and sadness. Movement smoothness was similar between anger and joy. The present findings are consistent with sit-to-walk performed with emotion (Kang and Gross, 2015) and support the idea that movement smoothness, as assessed with normalized jerk score, increases with movement speed in whole-body movements.

Results for the effect of the target emotions on gait speed are in line with previous work (Michalak et al., 2009; Roether et al., 2009; Naugle et al., 2010; Naugle et al., 2011; Gross et al., 2012; Fawver et al., 2014; Stins et al., 2015). That is, gait speed increased for the high arousal emotions compared to sadness. The changes in the other spatiotemporal gait parameters for the target emotions corresponded to the changes in gait speed (Andriacchi et al., 1977).

Emotion affected linear movement smoothness in the anteroposterior and vertical directions but not in the mediolateral direction. Movement smoothness increased in the vertical direction in the whole-body center-of-mass, head, thorax and pelvis for anger and joy than for sadness, and increased in the anteroposterior direction in the head for neutral emotion, anger and joy than for sadness. Emotion affected angular movement smoothness in both the upper and lower limbs.

Movement smoothness increased in the hip and ankle for anger than for sadness, and increased in the shoulder for anger and joy compared to sadness. In sum, emotion affected both linear and angular movement smoothness, and increases in movement smoothness were associated with high arousal emotions for both pleasant and unpleasant valences.

Our findings suggest that emotional arousal may be a stronger influence on movement smoothness than valence. Movement smoothness was similar between the high arousal and unpleasant valence of anger and the high arousal and pleasant valence of joy, but was different between the high arousal and unpleasant valence of anger and the low arousal and unpleasant valence of sadness. These findings are in line with previous work (Kang and Gross, 2015). Although only four target emotions were included and movements were limited to gait and sit-to-walk, the consistent findings suggest that emotional arousal may be a particularly potent factor associated with changes in coordination during emotionally expressive movements.

We found that linear movement smoothness in the vertical direction changed the most with emotions, and did not change at all in the mediolateral direction. It may be that emotion-related body movements in the vertical direction were less constrained by the locomotion task compared to balance constraints that may have restricted emotion-related changes in the mediolateral direction. However, emotion affected smoothness in the head in both the anteroposterior and vertical directions, unlike in the other segments. Head stabilization is one of the most important tasks for postural control during gait (Pozzo et al., 1990), so motions of the head compared to the center-of-mass, thorax or pelvis may have served sensory as well as expressive demands during emotional gait. The lack of difference in smoothness in the mediolateral direction among the target emotions is consistent with previous work (Kang and Gross, 2015).

We observed that movement smoothness increased for the high arousal emotions with faster gait speeds. Thus it needs to be considered whether movement smoothness during emotional gait is due solely to gait speed or whether there is a differential effect of emotion independent of gait speed. Several studies have reported speed effects on movement smoothness during gait in healthy young adults. Consistent with our findings, others have shown that movement smoothness decreased from normal to slow gait speeds for the head and pelvis in the anteroposterior and vertical directions (Menz et al., 2003) and for the whole-body center-of-mass in the anteroposterior and vertical directions (Brach et al., 2010), with jerk measured by harmonic ratio (derived from acceleration curves). In contrast to our results, however, Menz et al. (2003) found that movement smoothness also decreased as gait speed increased from normal to fast speeds. Using jerk ratio (anteroposterior/vertical), Brodie et al. (2014) also found that movement smoothness for the head peaked during gait at normal speed, but decreased at faster gait speeds. Thus, the decrease in movement smoothness with sad emotion in our study is consistent with the decrease in movement smoothness accompanying slower than normal gait speeds in other studies, but the increase in movement smoothness with anger and joy is not consistent with the decrease in movement smoothness at faster than normal gait speeds reported in other studies.

What is most notably different in our results from these previous studies is that movement smoothness during gait increased with gait speed for both anger and joy, suggesting that movement smoothness may manifest emotional effects beyond speed effects. We normalized jerk by movement time and amplitude to minimize the confounding effects (Hogan and Sternad, 2009), which further supports our suggestion that movement smoothness may be affected by emotion and not just gait speed. Additionally, we did not observe the effects of speed on movement smoothness in the anteroposterior direction (except for the head) that would be predicted by other studies,

further supporting the effect of emotion rather than speed on movement smoothness. Based on a measure of smoothness that normalizes for movement time and amplitude, our results suggest that the high arousal emotions produce highly coordinated, smooth whole-body movements.

We observed that emotional effects on center-of-mass movements are manifested in the same way as movements in individual segments, that is, smooth movement for anger and joy, and jerky movement for sadness. These findings suggest that emotion coordinates movements of body segments in the same way as the whole-body center-of-mass movements. If this result is robust for other movement tasks, it implies that the effect of emotion on movement smoothness could be assessed using data from either body segments or the center-of-mass.

Our findings may have clinical implications for assessing jerky movements in older adults (Brodie et al., 2014), and individuals with Parkinson's disease (Seidler et al., 2001), Huntington's disease (Smith et al., 2000) and stroke (Rohrer et al., 2002). Since our results suggest smooth movement while feeling joy, emotional manipulations like recalling joyful memories may be useful for improving movement smoothness for these populations. Additionally, movement smoothness may be an indicator reflecting emotional states in individuals with emotional disorders like major depression and bipolar disorder.

A limitation in this study is that we did not measure emotional arousal or valence directly. Based on the circumplex model in which emotions are categorized as high or low arousal and pleasant or unpleasant valence (Russel, 1980), we assumed participants had higher levels of arousal when feeling anger and joy than when feeling sadness. Because participants felt the target emotions "quite a bit", we believed that it was reasonable to assume participants' arousal was higher for anger and joy than for sadness.

In conclusion, emotion is associated with changes in movement smoothness during gait. The effect of emotion on movement smoothness was manifested primarily in the vertical direction in the whole-body center-of-mass, head, thorax and pelvis. In the limb movements, the effect of emotion on movement smoothness was manifested only in the hip, ankle and shoulder. Emotional arousal affects movement smoothness more strongly compared to valence. Since we used normalized jerk, emotional effects on movement smoothness may be beyond speed effects. Our findings suggest that movement smoothness is an important feature of emotion embodiment that can be investigated in future studies.

CHAPTER 4

GAIT CHARACTERISTICS ACROSS MOOD PHASES IN BIPOLAR DISORDER

4.1 Abstract

This study aimed to investigate the effect of mood phase on gait characteristics using biomechanical analysis for individuals with bipolar disorder. Four hypomanic, seven euthymic and 11 depressed individuals with bipolar disorder and 14 healthy controls performed gait at self-selected comfortable, slow and fast speeds. Kinematic and kinetic data were collected concurrently using a 16-camera optoelectronic motion capture system and two force plates. Spatiotemporal gait parameters, sagittal joint ranges of motion, upper body posture, the whole-body center-of-mass movement and smoothness, and peak ground reaction forces, and peak lower extremity joint torques and power generation were compared between groups. Gait speed, peak vertical ground reaction forces and peak ankle power generation for individuals in the hypomanic phase were more than 28%, 18% and 50% greater compared to individuals in depressed and euthymic phases, and healthy controls, respectively. These results suggest that gait biomechanics for individuals in the hypomanic phase are consistent with the qualitative clinical descriptions of hypomania, i.e., increased activity/energy. In contrast, individuals in the depressed phase walked at similar speeds and had similar ground reaction forces and power compared to individuals in the euthymic phase

and healthy controls, suggesting that gait biomechanics during the depressed phase are less related to clinical symptoms. Although gait speeds were similar for individuals in the euthymic phase and healthy controls, stride length, cadence, hip range of motion and vertical center-of-mass movement and peak hip power generation were greater for individuals in the euthymic phase compared to healthy controls, suggesting that the euthymic gait pattern had increased movement amplitude like hypomania but without the greater ground reaction forces and ankle power. These findings show that biomechanical analysis of gait can detect mood phase differences for individuals with bipolar disorder, and demonstrate for the first time that symptoms of excess "energy" in hypomania are reflected in higher force exertion and ankle power generation during gait.

4.2 Introduction

Bipolar disorder, formerly known as manic-depressive disorder, is a debilitating mental illness that is defined by periods of abnormally and persistently elevated mood (mania/hypomania) and periods of depression (depression) (American Psychiatric Association, 2013). Statistics show that lifetime and 12-month prevalence of bipolar disorder are 4.4 and 2.4%, respectively, among U.S. adults (Merikangas et al., 2007). According to the World Health Organization (WHO), globally, bipolar disorder affects approximately 30 million people, and is the 12th leading cause of disability (WHO the Global Burden of Disease: 2004 Update). In addition, in high-income countries (gross national income per person of $10,066 or more), bipolar disorder is the 6th leading cause of disability in people of ages 0-59 (WHO the Global Burden of Disease: 2004 Update). Among behavioral healthcare diagnoses such as substance abuse disorders, mood disorders or attention deficit hyperactivity disorders (ADHD), annual out-of-pocket costs for individuals with

bipolar disorder are more than twice those of any other behavioral health care diagnosis (Peele et al., 2003).

Abnormalities in motor behavior are important criteria for a diagnosis of bipolar disorder (National Institute of Mental Health, 2016). *The Diagnostic and Statistical Manual of Mental Disorders* (5th ed.: DSM-5) emphasizes increased activity/energy or psychomotor agitation as core symptoms for defining mania/hypomania, and having loss of energy or psychomotor retardation as core symptoms for defining depression (American Psychiatric Association, 2013). The evaluation of these behavioral symptoms during clinic visits are based on clinician- and patient-based descriptions (i.e., clinical interviews and self-report questionnaires) (Hamilton, 1960; Young et al., 1978; Spitzer et al., 1992; Altman et al., 1997; Kroenke et al., 2001; Rush et al., 2003), and the self-described symptoms are used in the diagnosis of bipolar disorder. However, the evaluations used in clinical interviews or self-questionnaires are subjective and qualitative, including descriptions like "subjectively increased motor activity-energy" (Young et al., 1978), "I have often been more active than usual" (Altman et al., 1997), "loss of energy" and "slight psychomotor retardation" (Hamilton, 1960).

Since descriptions used in clinical interviews and self-questionnaires are subjective, bipolar individuals may inaccurately report their motor behavior, resulting in clinicians' inaccurately perceiving behavioral symptoms. In fact, several studies have reported discrepancies between objective evaluation and self-reports for cognitive function in individuals with bipolar disorder (Burdick et al., 2005; Martínez-Arán et al., 2005; Svendsen et al., 2012). For example, Burdick et al. (2005) evaluated cognitive impairments for 37 individuals with bipolar disorder in various mood phases (hypomanic, euthymic, depressed and mixed phase) using self-reported questionnaires such as the Cognitive Failure Questionnaire (Broadbent et el., 1982) and a series of

objective neuropsychological tests such as the Stroop Color-Word Test (Stroop, 1935). They found that self-reported cognitive impairments were poorly correlated with objective cognitive impairments (i.e., individuals that reported more severe cognitive impairments performed better on objective neuropsychological tests). Moreover, descriptions used for the diagnosis of bipolar disorder are qualitative such as "slight psychomotor retardation" (Hamilton, 1960) and "moving so slowly" (Kroenke et al., 2001), which are not precise and could be biased by bipolar individuals in subjective self-reports. Obtaining quantitative data regarding motor behavior for bipolar disorder will be beneficial for more precisely and reproducibly measuring abnormalities in motor behavior and more accurately understanding how mood phase in bipolar disorder affects the ability to carry out daily activities. Furthermore, quantification of motor behavior associated with mood phase may eventually help to better understand the heterogeneous nature of bipolar disorder.

Although abnormal motor behavior is an important clinical symptom for bipolar disorder, quantified characteristics of motor behavior in bipolar disorder are found in only a few studies. Hausdorff et al. (2004) examined spatiotemporal gait characteristics for individuals with bipolar disorder and major depressive disorder, and healthy controls. They found that individuals with bipolar disorder and major depressive disorder walked with larger swing time variability, and tended (not significantly) to walk slower than healthy controls. Mood phase for participants with bipolar disorder was not reported. Lohr and Caligiuri (2006) examined force steadiness during a finger flexion task and velocity scaling during wrist movements in individuals with bipolar disorder and healthy controls. They reported that individuals with bipolar disorder performed worse in upper-extremity motor tasks that required force steadiness or scaling of movement velocity compared to healthy controls. Again, mood phase for participants with bipolar disorder was not reported. Bolbecker et al. (2011) investigated postural sway during quiet standing for

bipolar disorder. They found that individuals with bipolar disorder in euthymia (i.e., relatively normal mood phase of bipolar disorder) had greater sway area, and more fluctuation in the mediolateral direction compared to healthy controls. Lage et al. (2013) studied a goal-directed movement using a digitizer pen for individuals with bipolar disorder in euthymic phase. They found that euthymic bipolar disorder was associated with jerkier movement and more reliance on visual feedback during a goal-directed manual movement compared to healthy controls.

These studies pioneered the effort to more precisely understand motor behavior in bipolar disorder by using quantitative assessments, but their findings are limited. Most importantly, it is still uncertain whether the reported behavioral characteristics are mood-specific because mood phase information was not provided in some of the studies (Hausdorff et al., 2004; Lohr and Caligiuri, 2006). In the other studies, bipolar disorder individuals in only the euthymic phase were included (Bolbecker et al., 2011; Lage et al., 2013). To improve potential clinical applications, studies of motor behavior in bipolar disorder should include participants across bipolar disorder mood phases while investigating motor behavior with biomechanical assessments.

Gait is a day-to-day task that is both functional and emotionally expressive. Studies have demonstrated the effect of feeling emotion on quantified gait characteristics using biomechanics variables like gait speed, head flexion angle and movement jerk in healthy individuals (Michalak et al., 2009; Roether et al., 2009; Gross et al., 2012; Barliya et al., 2013; Kang and Gross, 2016). For example, when emotion was evoked using autobiographical memory, gait speed increased approximately 23% for joy compared to sadness, head angle was approximately 10° more flexed for sadness compared to joy, and changes in head flexion angle due to emotion were independent of changes in gait speed (Gross et al., 2012). In addition, movement jerk, a measure of decreased movement smoothness, was approximately 26% greater for sadness compared to joy (Kang and

Gross, 2016). Although the effect of emotion on gait performance in healthy individuals may not be the same as the effect of mood phase on gait performance in individuals with bipolar disorder, it is reasonable to anticipate that speed-related gait kinematics may be different between mood phases, based on clinical symptoms like psychomotor agitation for mania/hypomania and psychomotor retardation for depression (American Psychiatric Association, 2013). Also, it may be that force and power generation during gait may be related to high or low energy that individuals with bipolar disorder experience during mania/hypomania or depression, respectively. Thus, kinematic and kinetic measures during gait may be mood-specific clinical markers for bipolar disorder.

In this study, the effect of mood phase on gait was quantified using biomechanical analysis for individuals with bipolar disorder and healthy individuals. Mania/hypomania is characterized by psychomotor agitation and increased energy, depression is characterized by psychomotor retardation and decreased energy, and euthymia is a relatively normal mood phase (American Psychiatric Association, 2013). Therefore, it was hypothesized that gait kinematics and kinetics for mania/hypomania would be associated with faster speed, and higher force and power generation. It was also hypothesized that gait kinematics and kinetics for depression would be associated with slower speed, and lower force and power generation. Lastly, it was hypothesized that kinematic and kinetic gait characteristics for euthymia would be similar to healthy individuals. By comparing kinematic and kinetic characteristics of gait performance in individuals with bipolar disorder across mood phases with healthy individuals, the impact of mood phase on body movements in a day-to-day task and the feasibility of using gait performance as a mood-specific clinical marker for bipolar disorder can be assessed.

4.3 Materials and methods

4.3.1 Participants

Gait kinematics and kinetics were analyzed in this study as part of the baseline evaluation for an ongoing longitudinal study of motor behavior for assessing gait and sit-to-walk in individuals with bipolar disorder and healthy controls at baseline and follow-up testing sessions. The two testing sessions were approximately 6 months apart.

Twenty-six individuals with bipolar disorder and 14 healthy controls were recruited from an existing cohort enrolled in the Heinz C. Prechter Longitudinal Study of Bipolar Disorder at the University of Michigan. Diagnosis in all individuals in the study was confirmed using a clinical interview (i.e., the Diagnostic Interview for Genetic Studies) (Nurnberger et al., 1994). Included in this study were individuals with bipolar disorder that met the DSM-IV diagnostic criteria (American Psychiatric Association, 2000). Bipolar individuals with a history of schizophrenia or schizoaffective disorder, active substance use in the past 3 months, or a history of neurologic or orthopedic illness that might affect gait were excluded. In addition, healthy controls with no personal history of mood disorder, schizophrenia, substance dependence, or neurologic or orthopedic illness that might affect gait, and no family history of mood disorder were included in this study.

The University of Michigan Institutional Review Board approved the protocol. Each participant gave written informed consent before beginning the experiment and earned $30 for their participation in the baseline testing session.

4.3.2 Assessment of mood phase

After signing written informed consent, each participant completed two questionnaires for assessing current mood phase: (1) Patient Health Questionnaire (PHQ-9) (Kroenke et al., 2001) and (2) Altman Self-Rating Mania Scale (ASRM) (Altman et al., 1997). In addition, each participant completed the suicide item on the 16-item Quick Inventory of Depressive Symptomatology (QIDS) in self-report form (Rush et al., 2003) as a screen for suicide risk.

Scores on the PHQ-9 and the ASRM were used to classify individuals with bipolar disorder by phases into hypomanic (PHQ-9 < 6 and ASRM ≥ 6), euthymic (PHQ-9 < 6 and ASRM < 6), depressed (PHQ-9 ≥ 6 and ASRM < 6) and mixed (PHQ-9 ≥ 6 and ASRM ≥ 6) groups. Among 26 individuals with bipolar disorder, four individuals were in a hypomanic phase, eight individuals were in a euthymic phase, twelve individuals were in a depressed phase, and two individuals were in a mixed phase. In addition, three individuals in depressed phase reported suicidal thought ("I thought of suicide or death several times for several minutes over the past 7 days.") according to the suicide item on the QIDS, which prompted safety assessment by a study psychiatrist.

4.3.3 Assessment of gait kinematics and kinetics

A 16-camera optoelectronic 3D motion capture system (Motion Analysis Corporation, Santa Rosa, CA, USA) was used to obtain motion data. Camera-based optoelectronic motion capture technology is a validated gold standard method for studying human movement, and was used previously for investigating movement in individuals with psychiatric disorders (Michalak et al., 2009; Stensdotter et al., 2012; Stensdotter et al., 2013; Kaletsch et al., 2014a; Kaletsch et al.,

2014b) or investigating emotional effects on movement in healthy individuals. Briefly, participants changed into tight-fitting clothing with walking shoes after completing the questionnaires. Then, non-invasive retroreflective markers were attached to each participant's body using double-sided tape or velcro (Fig. 4.1). Data were collected from the reflective markers at 120 Hz, and were filtered at 6 Hz using a 4^{th}-order Butterworth low-pass filter. In addition to the marker data, ground reaction forces were collected using two force plates (Advanced Mechanical Technology Inc., Watertown, MA, USA; width x length = 502 mm x 502 mm) that were synchronized to the motion capture system at 1200 Hz, and were filtered at 50 Hz using a 4^{th}-order Butterworth low-pass filter.

Prior to performing motion trials, participants were asked to walk back and forth across the laboratory several times so that they felt comfortable with the clothing and laboratory settings. For gait trials, each participant was asked to walk on an 8-meter walkway at self-selected comfortable, slow and fast speeds. The two force plates were embedded in the middle of the walkway. Participants performed gait for each speed condition until five successful trials in which each participant made foot contact with a force plate without any notable changes in gait pattern were obtained. The order of speed conditions was comfortable, slow and fast, and was the same across all participants.

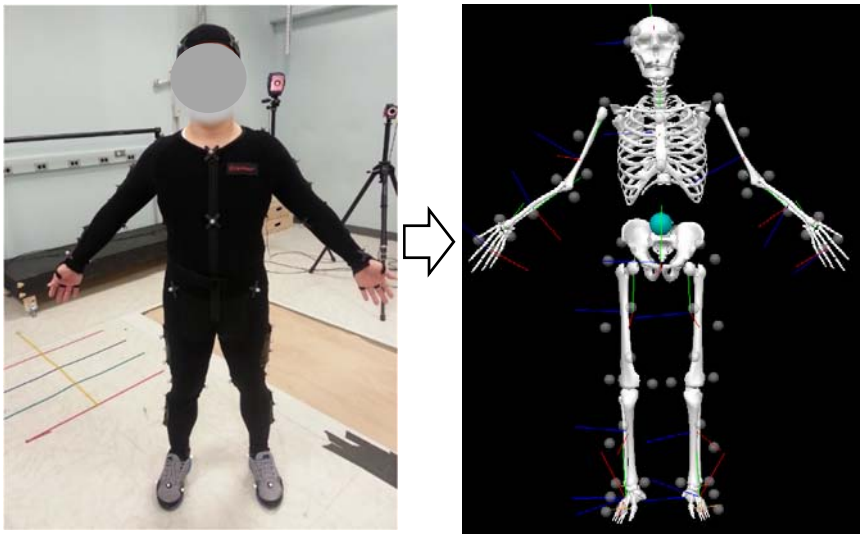

Fig. 4.1. Retroreflective markers attached on each participant's body were used to build a biomechanical human model and track body movements. The green sphere in the center of the biomechanical model represents the whole-body center-of-mass of the human model.

4.3.4 Data analysis

Kinematic and kinetic data were generated using Visual3D biomechanics software (C-Motion Inc., Germantown, MD USA). Specifically, a 15-segment biomechanical human model that consisted of the head, thorax, upper arms, forearms, hands, pelvis, thighs, shanks, and feet was created using anthropometric measurements and the location of the retroreflective markers in a static reference trial. In addition, the whole-body center-of-mass position was computed for the human model (Fig. 4.1).

Since a primary goal of this study was to assess force and power generation, gait analysis was performed on gait cycles in which data from a force plate were available. Typically, force data were available for only one gait cycle in each trial. For the kinematic gait analysis, one gait cycle was identified using a kinematic method (Zeni et al., 2008). Then, for the identified gait cycle, spatiotemporal gait parameters were calculated including gait speed, stride length, cadence and the

percentage of double limb support, upper body posture of the head and thorax (i.e., mean angle in the flexion-extension direction), and joint ranges of motion in the sagittal plane for the shoulder, elbow, wrist, hip, knee and ankle. The center-of-mass displacement and center-of-mass smoothness were computed in the anteroposterior, vertical and mediolateral directions. The center-of-mass smoothness was computed as jerk (J, m/s^3; the first time derivative of acceleration) normalized to center-of-mass displacement (D) and stride time (T) (Eq. 1) (Hogan and Sternad, 2009; Kang and Gross, 2015; Kang and Gross, 2016). Higher values of the normalized jerk score indicated lesser smoothness in center-of-mass movement.

$$\text{Normalized jerk score} = \sqrt{\frac{1}{2} \cdot \frac{T^5}{D^2} \cdot \int J^2 dt} \text{ (no units)} \quad \text{(Eq.1)}$$

For the kinetic gait analysis, an automatic gait event detection function based on ground reaction force data in Visual3D was used to identify stance phase for each gait trial. Then, for the identified stance phase, peak positive and negative ground reaction forces in the anteroposterior direction, and the 1st and 2nd peaks, and the valley between the ground reaction force peaks in the vertical direction were calculated. In addition, joint torques and powers in the hip, knee and ankle were computed using inverse dynamics analysis with Visual3D. Then, peak flexion and extension torques for the hip and knee, peak dorsiflexion and plantarflexion torques in the ankle, and peak power generation in the hip, knee and ankle were identified. All outcome variables in kinetic gait analysis were normalized to body weight.

4.3.5 Statistical analysis

For each participant, mean values across gait trials for each speed condition were calculated for each outcome variable. Then, for each group, mean values and standard deviations across participants for each speed condition were calculated.

Multiple comparisons using one-way ANOVA with Tukey post-hoc analyses were used to test significant differences in mean values between the groups (hypomanic, euthymic, depressed and healthy) ($p < 0.05$). Since many of the kinematic and kinetic variables are correlated with gait speed (Andriacchi et al., 1977; Kirtley 1985; Winter, 1985; Öberg et al., 1994; Keller et al., 1996; Chen et al., 1997; Lelas et al., 2003; Orendurff et al., 2003), gait speed was considered as covariate. Thus, a linear mixed model with random effects of participant and fixed effects of gait speed and group was used to further test significant differences in kinematic and kinetic variables between the groups with separated effects of gait speed ($p < 0.05$). Effect size was calculated as Cohen's d ($d < 0.2$ as a small effect; $0.2 \leq d < 0.8$ as a medium effect; $0.8 \leq d$ as a large effect). Additionally, Fisher's exact test was used to compare differences for medications and other psychiatric comorbidities between the hypomanic, euthymic and depressed groups.

4.4 Results

4.4.1 Participant characteristics

Among the 26 participants with bipolar disorder, five individuals were excluded from the analysis. In the depressed group, one participant was excluded because of protocol violation and another was excluded because of reports of pain and a limping gait. One participant was excluded from the euthymic group because of apparent thoracic kyphosis. Two other participants with bipolar disorder were excluded because they did not meet the criteria for hypomanic, euthymic or depressed phases. As a result, data from 21 individuals with bipolar disorder (four in hypomania; seven in euthymia; ten in depression) and 14 healthy controls were included in the analyses (Table 4.1). The relationship between PHQ-9 and ASRM is shown in Fig. 4.2. There were no significant differences in age, weight, height, and body mass index (BMI) among the groups (Table 4.1) (all $p > 0.05$). Fisher's exact test showed non-significant differences for medications and other psychiatric comorbidities between the hypomanic, euthymic and depressed groups (all $p > 0.05$).

Table 4.1
Participant characteristics for individuals with bipolar disorder and healthy controls

	Hypomanic	Euthymic	Depressed	Healthy
N	4 (1 female)	7 (3 female)	10 (7 female)	14 (9 female)
Anthropometric characteristics, Mean (SD)				
Age (years)	45.0 (17.4)	34.4 (7.4)	38.4 (10.2)	42.2 (12.6)
Weight (kg)	73.4 (9.4)	75.4 (18.2)	78.2 (26.6)	73.3 (13.6)
Height (m)	1.74 (0.05)	1.73 (0.13)	1.69 (0.10)	1.69 (0.07)
BMI (kg/m^2)	24.2 (2.0)	24.9 (3.7)	27.3 (7.3)	25.6 (5.1)
Clinical characteristics, Mean (SD)				
PHQ-9	1.8 (1.5)	2.3 (1.4)	13.8 (7.1)	0.1 (0.4)
ASRM	12.5 (5.2)	2.4 (1.7)	2.0 (1.6)	1.1 (2.6)
Age of onset (years)	15.8 (8.1)	17.9 (3.6)	16.0 (6.0)	N/A
Years of illness (years)	31.8 (19.9)	19.6 (11.0)	22.2 (10.6)	N/A
Medication, N				
None	0	1	1	N/A
Lithium	2	4	3	N/A
Anticonvulsant [a]	2	3	5	N/A
Antipsychotic [b]	2	3	6	N/A
Antidepressant [c]	1	2	5	N/A
Sedative-hypnotic [d]	1	0	4	N/A
Comorbid psychiatric disorder, N				
ADHD	1	1	2	N/A
Anxiety disorder	2	2	5	N/A
Substance use disorder (past)	3	4	6	N/A
Post-traumatic stress disorder	0	1	1	N/A

Note: There were no significant differences in age, weight, height and BMI between groups.

[a] Anticonvulsant medication includes gabapentin (two in depression), lamotrigine (two in hypomania; one in euthymia; three in depression), topiramate (one in depression) and valproate (two in euthymia).

[b] Antipsychotic medication includes aripiprazole (two in depression), asenapine (one in depression), lurasidone (one in euthymia; two in depression), olanzapine (one in hypomania), perphenazine (one in hypomania), quetiapine (one in depression), risperidione (one in euthymia) and ziprasidone (one in euthymia).

[c] Antidepressant medication includes bupropion (one in hypomania; two in euthymia; two in depression), citalopram (one in depression), nortriptyline (one in depression), trazodone (one in depression), venlafaxine (one in depression) and vortioxetine (one in depression).

[d] Sedative-hypnotic medication includes alprazolam (one in hypomania), clonazepam (three in depression) and diazepam (one in depression).

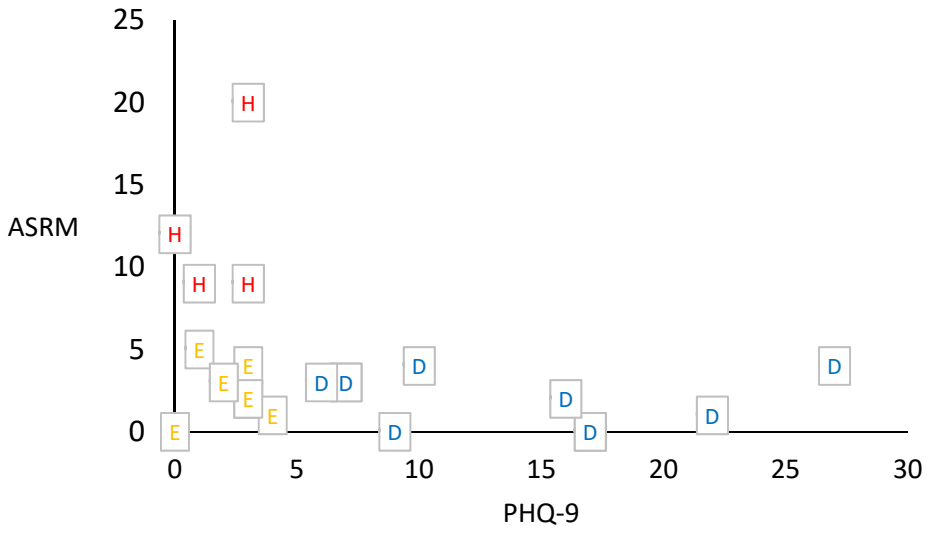

Fig. 4.2. The relationship between PHQ-9 and ASRM for 21 individuals with bipolar disorder. Each letter represents one participant. Letters represent the following: H for hypomanic groups, E for euthymic group and D for depressed group. Two sets of two depressed individuals had same PHQ-9 scores and ASRM scores (PHQ-9 = 7 / ASRM = 3; PHQ-9 = 17 / ASRM = 0).

4.4.2 Spatiotemporal gait parameters

4.4.2.1 Gait speed

Gait speed tended to be greater for hypomanic group than for euthymic and depressed groups and healthy controls for all speed conditions, but the differences were significant only for the comfortable speed condition (Table 4.2). Comfortable gait speed was 28.1, 34.8 and 28.1% greater for the hypomanic group than for the euthymic group, the depressed group and healthy controls, respectively (all $p < 0.05$; $d = 2.3$, 1.4 and 2.8, respectively).

Table 4.2
Mean gait speed (m/s) for each speed condition and group

	Hypomanic	Euthymic	Depressed	Healthy
Speed condition				
Slow	1.00 (0.21)	0.75 (0.19)	0.74 (0.27)	0.74 (0.17)
Comfortable	1.55 (0.15)^{HC*,EU*,DP**}	1.21 (0.12)^{HM*}	1.15 (0.28)^{HM**}	1.21 (0.12)^{HM*}
Fast	2.03 (0.18)	1.71 (0.17)	1.79 (0.23)	1.84 (0.28)

Note: Values in parentheses are standard deviations. Superscript letters are significant differences between groups based multiple comparisons using one-way ANOVA with Tukey post-hoc analysis: HM=Hypomanic, EU=Euthymic, DP=Depressed, HC=Healthy. * $p < .05$. ** $p < .01$.

The relative changes in gait speed were not significantly different among the groups for any of the speed conditions (i.e., slow to comfortable, comfortable to fast or slow to fast conditions) (all $p > 0.05$). For all groups, gait speed more than doubled (153.9 ± 79.4 %) from the slow to fast speed conditions, (Fig. 4.3). From the comfortable to slow speed conditions, gait speed decreased 38.0 ± 11.4 %, and from the comfortable to fast speed conditions, gait speed increased 50.5 ± 26.8 % across groups (Fig. 4.3).

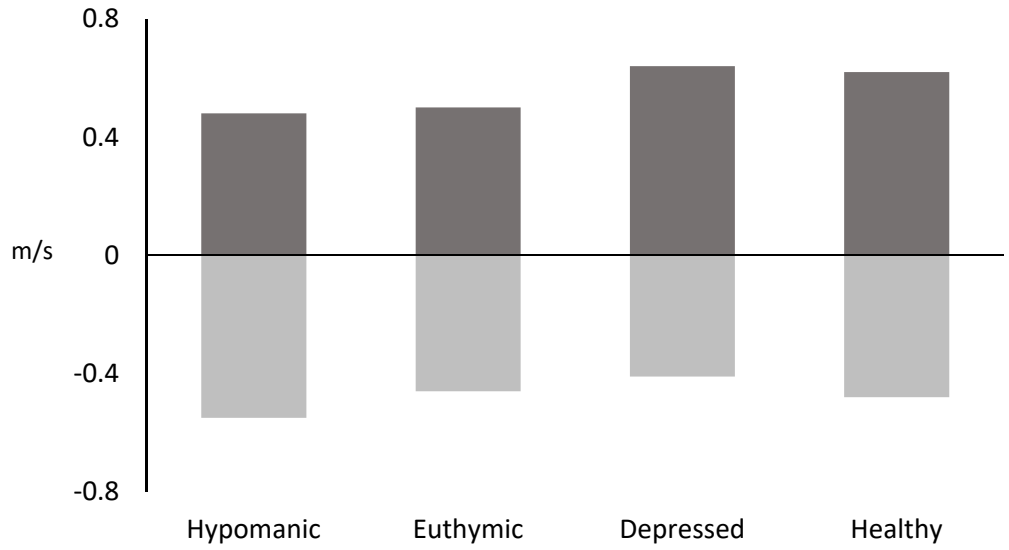

Fig. 4.3. The increases in gait speed from the comfortable speed condition to the fast speed condition (positive values) and the decrease in gait speed from the comfortable speed condition to the slow speed condition (negative values) for each group. Changes in gait speed between the speed conditions were not significantly different between groups.

4.4.2.2 Relationship between clinical scores and gait speed

The relationships between clinical scores and gait speed are shown for each speed condition in Fig. 4.4. For all speed conditions, gait speed was significantly correlated with ASRM scores (all $p < 0.05$) but was not related to PHQ-9 scores (all $p > 0.05$).

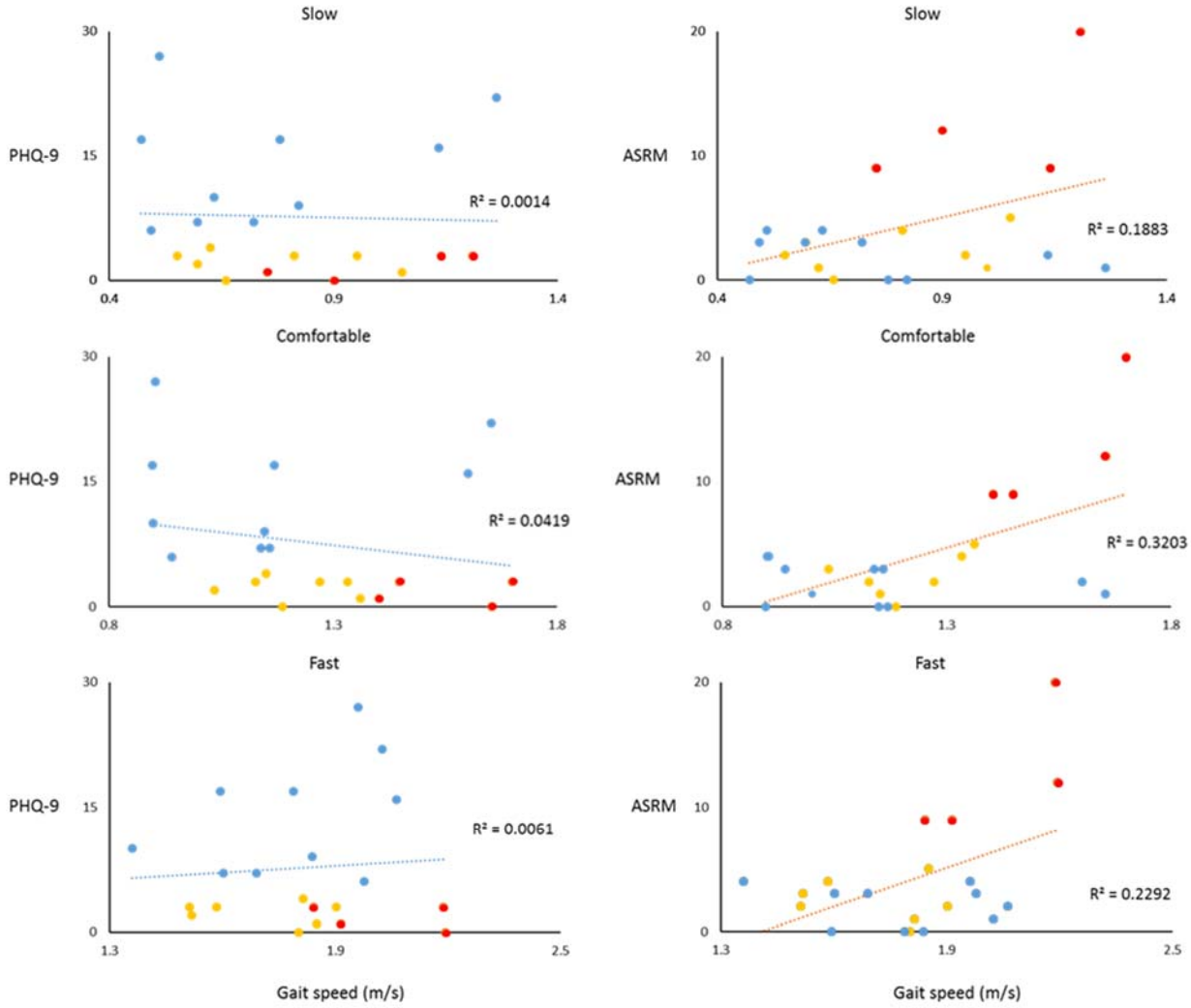

Fig. 4.4. The relationships between PHQ-9 (left column) and ASRM (right column), and gait speed for the slow (top row), comfortable (middle row) and fast (bottom row) speed conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group and blue for the depressed group. R^2 represents the coefficient of determination.

Because the mean gait speeds for two individuals in the depressed group were more than 4 standard deviations from the other depressed individuals, and even greater than individuals in the hypomanic group (Fig. 4.4), the impact of their inclusion in the depressed group was further investigated. The mean gait speeds for the two "fast" depressed and the other eight "slow" depressed individuals were 1.20 ± 0.09 and 0.63 ± 0.14 m/s, respectively, for the slow speed condition, 1.63 ± 0.04 and 1.03 ± 0.13 m/s, respectively, for the comfortable speed condition, and 2.04 ± 0.03 and 1.84 ± 0.28 m/s, respectively, for the fast speed condition. Furthermore, when gait speeds were compared between the "slow" depressed subgroup that excluded the two "fast" depressed individuals and the other groups, significant differences emerged. Specifically, the mean gait speed for the "slow" depressed subgroup was 37.0% less than for the hypomanic group for the slow speed condition ($p < 0.05$), and was 33.5, 14.9 and 14.9% less than for the hypomanic group, the euthymic group and healthy controls (all $p < 0.05$), respectively, for the comfortable speed condition, when compared using one-way ANOVA with Tukey post-hoc analysis. The significant differences for mean gait speed between the "slow" depressed subgroup and the hypomanic group for the slow speed condition, and between the "slow" depressed subgroup, and the euthymic group and healthy controls for the comfortable speed condition were not observed when the two "fast" depressed individuals were included in the depressed group.

The relationships between clinical scores and gait speed after excluding the two "fast" depressed individuals were also investigated (Fig. 4.5). When the two "fast" depressed individuals were excluded, a significant relationship emerged between gait speed and PHQ-9 scores for the comfortable speed condition ($R^2 = 0.358$, $p < 0.05$) for the "slow" depressed subgroup that did not exist for the depressed group that included the two "fast" depressed individuals. The relationship between gait speed and ASRM scores was strengthened for the "slow" depressed subgroup

compared to the depressed group that included the two "fast" depressed individuals, resulting in higher correlation coefficients. For example, the R^2 values increased from 0.188 to 0.426 for the slow speed condition, from 0.320 to 0.592 for the comfortable speed condition, and from 0.229 to 0.344 for the fast speed condition for the "slow" depressed subgroup compared to the depressed group that included the two "fast" depressed individuals (all $p < .05$).

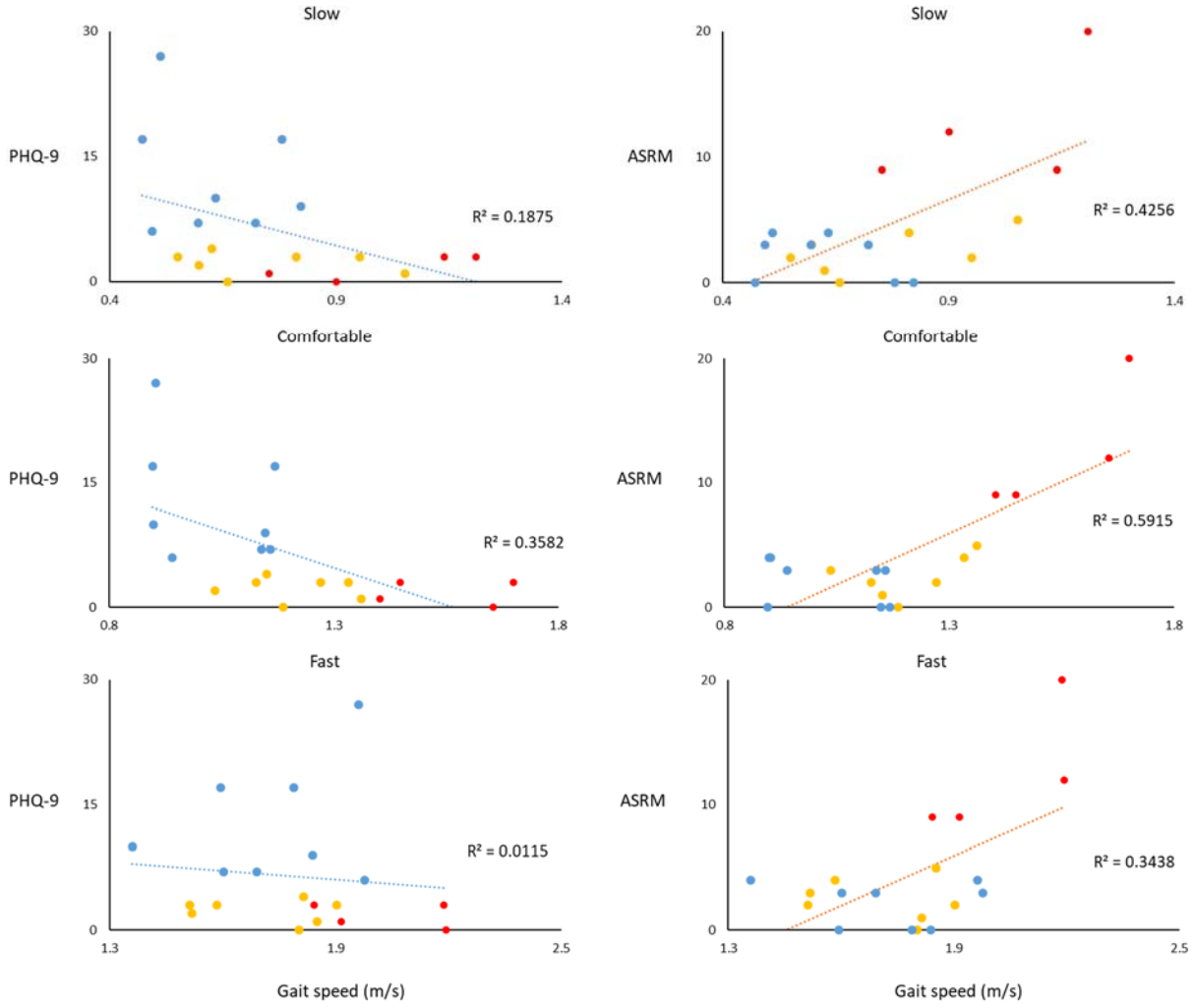

Fig. 4.5. The relationships between PHQ-9 (left column) and ASRM (right column), and gait speed without the two "fast" depressed individuals for the slow (top row), comfortable (middle row) and fast (bottom row) speed conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group and blue for the depressed group. R^2 represents the coefficient of determination.

4.4.2.3 Stride length, cadence and double limb support

As expected with change in gait speed, stride length increased for the fast speed condition and decreased for the slow speed condition for all groups (Table 4.3). For the comfortable speed condition, stride length was 20.8 and 17.2% greater for the hypomanic group than for the depressed group and healthy controls, respectively (all $p < 0.05$; $d = 1.5$ and 2.3, respectively)). For the fast and slow speed conditions, however, differences in stride lengths between groups were not significant.

Few differences in cadence and double limb support emerged between groups. Although cadence tended to be faster for the hypomanic group than for the other groups, the difference was significant only for the euthymic group for the comfortable speed condition (17.5%; $p < 0.05$; $d = 2.1$) (Table 4.3). Double limb support tended to be least for the hypomanic group for the comfortable and slow speed conditions, but the difference was significant only for the depressed group for the comfortable speed condition (16.2%; $p < 0.05$; $d = 1.4$).

Table 4.3

Mean values for stride length, cadence and double limb support for each speed condition and group

	Hypomanic	Euthymic	Depressed	Healthy
Slow				
Stride length (m)	1.28 (0.11)	1.16 (0.15)	1.08 (0.21)	1.08 (0.14)
Cadence (steps/min)	93.1 (13.1)	76.4 (11.0)	81.1 (15.1)	80.8 (12.2)
Double limb support (%)	31.8 (3.3)	35.6 (0.0)	37.3 (5.9)	37.2 (5.4)
Comfortable				
Stride length	1.57 (0.04)^{HC*,DP**}	1.44 (0.10)	1.30 (0.18)^{HM**}	1.34 (0.10)^{HM*}
Cadence	118.8 (8.7)^{EU*}	101.1 (8.4)^{HM*}	105.2 (10.8)	108.6 (7.7)
Double limb support	25.9 (1.7)^{DP*}	28.4 (0.0)	30.1 (3.1)^{HM*}	29.1 (2.6)
Fast				
Stride length	1.79 (0.05)	1.72 (0.12)	1.66 (0.18)	1.64 (0.19)
Cadence	136.6 (10.0)	119.5 (10.7)^{HC*}	129.3 (6.8)	134.9 (15.0)^{EU*}
Double limb support	24.5 (1.1)	24.4 (0.0)	25.5 (2.7)	25.0 (2.8)

Note: Values in parentheses are standard deviations. Superscript letters are significant differences between groups based multiple comparisons using one-way ANOVA with Tukey post-hoc analysis: HM=Hypomanic, EU=Euthymic, DP=Depressed, HC=Healthy. * $p < .05$. ** $p < .01$.

The relationships between gait speed, and stride length, cadence and double limb support for each speed condition are shown in Fig. 4.6. For all speed conditions, stride length, cadence and double limb support depended on gait speed (all $p < 0.05$) (Table 4.4). The effect of gait speed and group on spatiotemporal gait parameters were separated using a linear mixed model (Table 4.4). Stride length was greater for the euthymic group than for the depressed group and healthy controls (all $p < 0.05$; $d = 0.8$ and 1.0, respectively), and cadence was less for the euthymic group than for the depressed group and healthy controls for the comfortable speed condition (all $p < 0.05$; $d = 0.4$ and 1.0, respectively). For the slow speed condition, stride length was greater for the euthymic

group than for the depressed group and healthy controls (all $p < 0.05$; $d = 0.4$ and 0.6, respectively), and cadence was less for the euthymic group than for healthy controls ($p < 0.05$; $d = 0.4$). For the fast speed condition, stride length was greater and cadence was less for the euthymic group than for healthy controls (all $p < 0.05$; $d = 0.4$ and 1.0, respectively). Double limb support was not significantly different between groups for any speed condition.

Table 4.4
Estimates and 95% confidence intervals for stride length, cadence and double limb support (DLS) based on the linear mixed model

	Gait speed	Healthy vs. Hypomanic	Euthymic vs. Hypomanic	Depressed vs. Hypomanic	Healthy vs. Euthymic	Depressed vs. Euthymic	Healthy vs. Depressed
Slow							
Stride length	**0.65***** **(0.60, 0.71)**	-0.03 (-0.11, 0.06)	0.05 (-0.05, 0.14)	-0.04 (-0.12, 0.05)	**-0.07*** **(-0.14, -0.004)**	**-0.08*** **(-0.15, -0.01)**	0.01 (-0.05, 0.07)
Cadence	**61.1***** **(57.04, 65.09)**	3.8 (-2.31, 9.85)	-1.4 (-8.09, 5.30)	3.7 (-2.64, 10.02)	**5.7*** **(0.27, 10.06)**	5.1 (-0.12, 10.29)	0.1 (-4.30, 4.45)
DLS	**-0.23***** **(-0.26, -0.20)**	-0.01 (-0.03, 0.02)	-0.02 (-0.05, 0.01)	-0.004 (-0.03, 0.03)	0.01 (-0.01, 0.04)	0.02 (-0.01, 0.04)	-0.002 (-0.02, 0.02)
Comfortable							
Stride length	**0.60***** **(0.54, 0.65)**	-0.02 (-0.10, 0.06)	0.08 (-0.01, 0.16)	-0.03 (-0.11, 0.06)	**-0.10**** **(-0.16, -0.03)**	**-0.10**** **(-0.17, -0.04)**	0.01 (-0.05, 0.06)
Cadence	**40. 8***** **(36.44, 45.11)**	3.6 (-2.48, 9.64)	-3.8 (-10.42, 2.91)	2.8 (-3.55, 9.19)	**7.3**** **(2.52, 12.14)**	**6.6*** **(1.45, 11.70)**	0.8 (-3.55, 5.07)
DLS	**-0.11***** **(-0.13, -0.09)**	-0.01 (-0.03, 0.02)	-0.01 (-0.04, 0.01)	-0.003 (-0.02, 0.02)	0.01 (-0.01, 0.02)	0.10 (-0.01, 0.03)	-0.003 (-0.02, 0.01)
Fast							
Stride length	**0.44***** **(0.39, 0.50)**	-0.06 (-0.19, 0.07)	0.08 (-0.06, 0.22)	-0.02 (-0.15, 0.12)	**-0.14*** **(-0.25, -0.04)**	-0.10 (-0.21, 0.02)	-0.05 (-0.14, 0.05)
Cadence	**36.2***** **(32.10, 40.33)**	5.4 (-4.85, 15.58)	-5.4 (-16.78, 5.88)	1.5 (-9.19, 12.15)	**10.8*** **(2.48, 19.14)**	6.9 (-1.93, 15.78)	3.9 (-3.56, 11.33)
DLS	**-0.06***** **(-0.07, -0.04)**	-0.01 (-0.03, 0.02)	-0.02 (-0.04, 0.01)	0.774 (-0.03, 0.03)	0.01 (0.00, 0.03)	0.02 (0.00, 0.03)	-0.002 (-0.02, 0.01)

Note: Values in parentheses are lower and upper bounds for 95% confidence intervals. Bold fonts with asterisks indicate significant differences between groups. * $p < .05$. ** $p < .01$. *** $p < .001$.

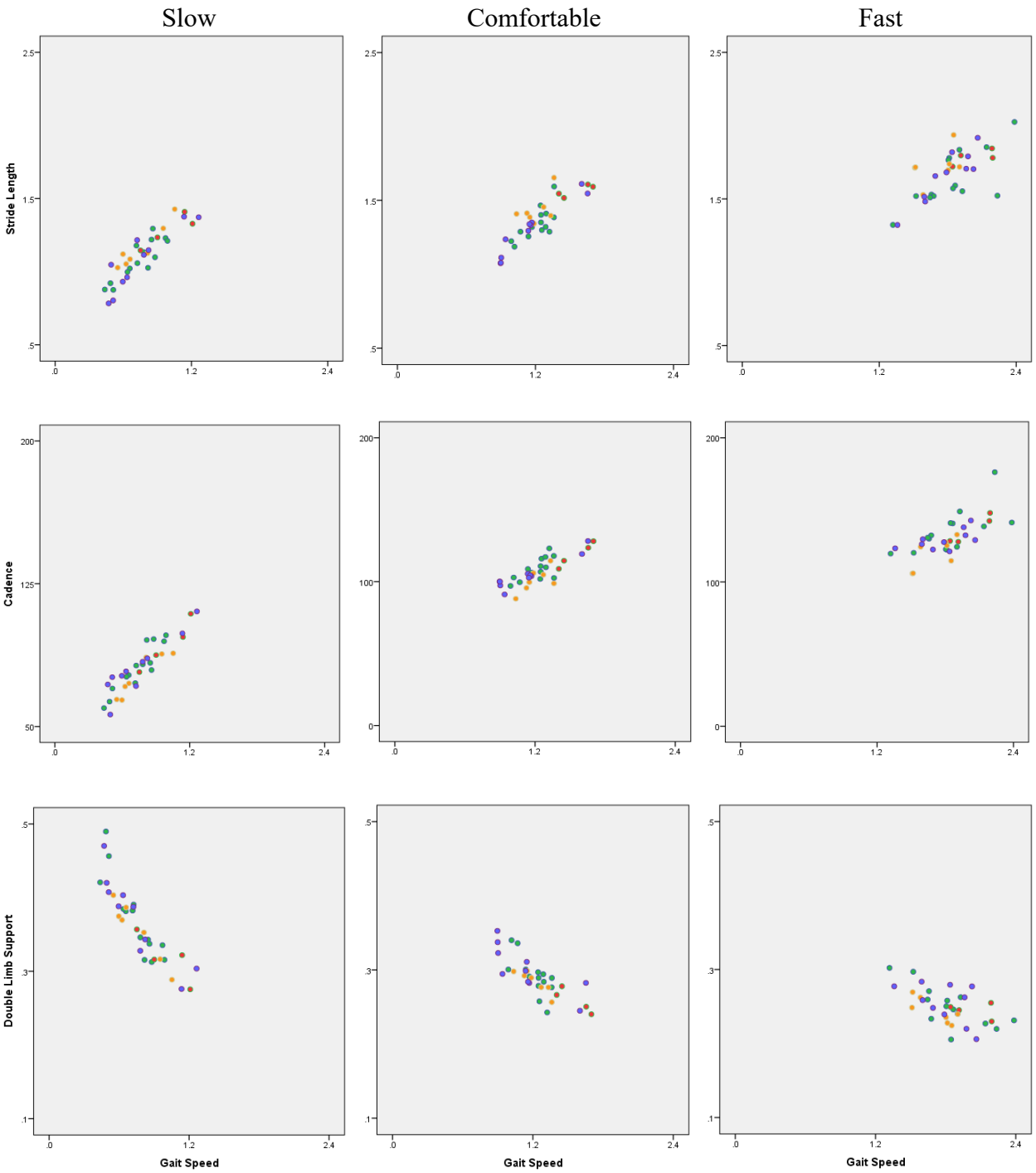

Fig. 4.6. The relationships between gait speed and stride length (top row), cadence (middle row) and double limb support (bottom row) for the slow (left column), comfortable (middle column) and fast speed (right column) conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group, blue for the depressed and green for healthy controls.

4.4.3 Kinematic gait analysis

4.4.3.1 Joint ranges of motion

Mean joint angles in the sagittal plane for each group during one gait cycle are shown for the comfortable speed condition in Fig. 4.7. Joint ranges of motion differed between groups for the comfortable and slow speed conditions (Table 4.5). In the upper extremity, significant differences between groups were found for wrist range of motion for the comfortable speed. Wrist range of motion was 6.4° and 5.6° greater for the hypomanic group than for the euthymic group and healthy controls, respectively, for the comfortable speed condition (all $p < 0.05$; $d = 1.5$ and 2.2, respectively). For the slow and fast speed conditions, no significant differences for wrist range of motion were found among the groups. Shoulder and elbow ranges of motion were not significantly different between groups.

In the lower extremity, significant differences between groups were found for hip range of motion for the comfortable and slow speed conditions (Table 4.5). For the comfortable speed condition, hip range of motion was 7.1° and 9.0° greater for the hypomanic group than for the depressed group and healthy controls, respectively (all $p < 0.05$; $d = 1.4$ and 2.9, respectively), and 6.8° greater for the euthymic group than for healthy controls ($p < 0.05$). For the slow speed condition, hip range of motion was 8.0° and 6.1° less for healthy controls than for the hypomanic group and the euthymic group for the slow speed condition (all $p < 0.05$; $d = 2.1$ and 1.4, respectively). Knee and ankle ranges of motion were not significantly different between groups.

The relationship between gait speed and ranges of motion in the upper and lower extremities for each speed condition are shown in Fig. 4.8 and Fig. 4.9, respectively. Joint ranges

of motion depended on gait speed (all $p < 0.05$) except for the shoulder and elbow for the comfortable speed condition, the wrist for all speed conditions, the knee for the fast speed condition and the ankle for the comfortable and fast speed conditions (Table 4.6). When the effect of gait speed was isolated using the linear mixed model, significant differences in ranges of motion were found between groups for the shoulder, wrist, hip and ankle (Table 4.6). Shoulder range of motion was less for the depressed group than for healthy controls for the slow speed condition ($p < 0.05$; $d = 0.8$). Wrist range of motion was greater for the hypomanic group than for the euthymic group and healthy controls for the comfortable speed condition (all $p < 0.05$). Hip range of motion was greater for the hypomanic group than for healthy controls ($p < 0.05$), and was 4.9° and 6.9° greater for the euthymic group than for the depressed group and healthy controls for the comfortable speed condition, respectively (all $p < 0.05$; $d = 1.0$ and 2.2, respectively). Hip range of motion was less for healthy controls than for the hypomanic group and the euthymic group for the slow speed condition (all $p < 0.05$). For the fast speed condition, hip range of motion was greater for the euthymic group than for the hypomanic group ($p < 0.05$; $d = 0.5$), and was less for healthy controls than for the euthymic group and the depressed group ($p < 0.05$; $d = 1.1$ and 0.6, respectively). Ankle range of motion was greater for the hypomanic group than for the depressed group for the comfortable speed condition ($p < 0.05$; $d = 1.5$), and was less for the euthymic group than for the hypomanic group and healthy controls for the slow speed condition ($p < 0.05$; $d = 1.3$ and 1.1, respectively). Elbow and knee ranges of motion were not significantly different between groups for any speed condition after accounting for gait speed.

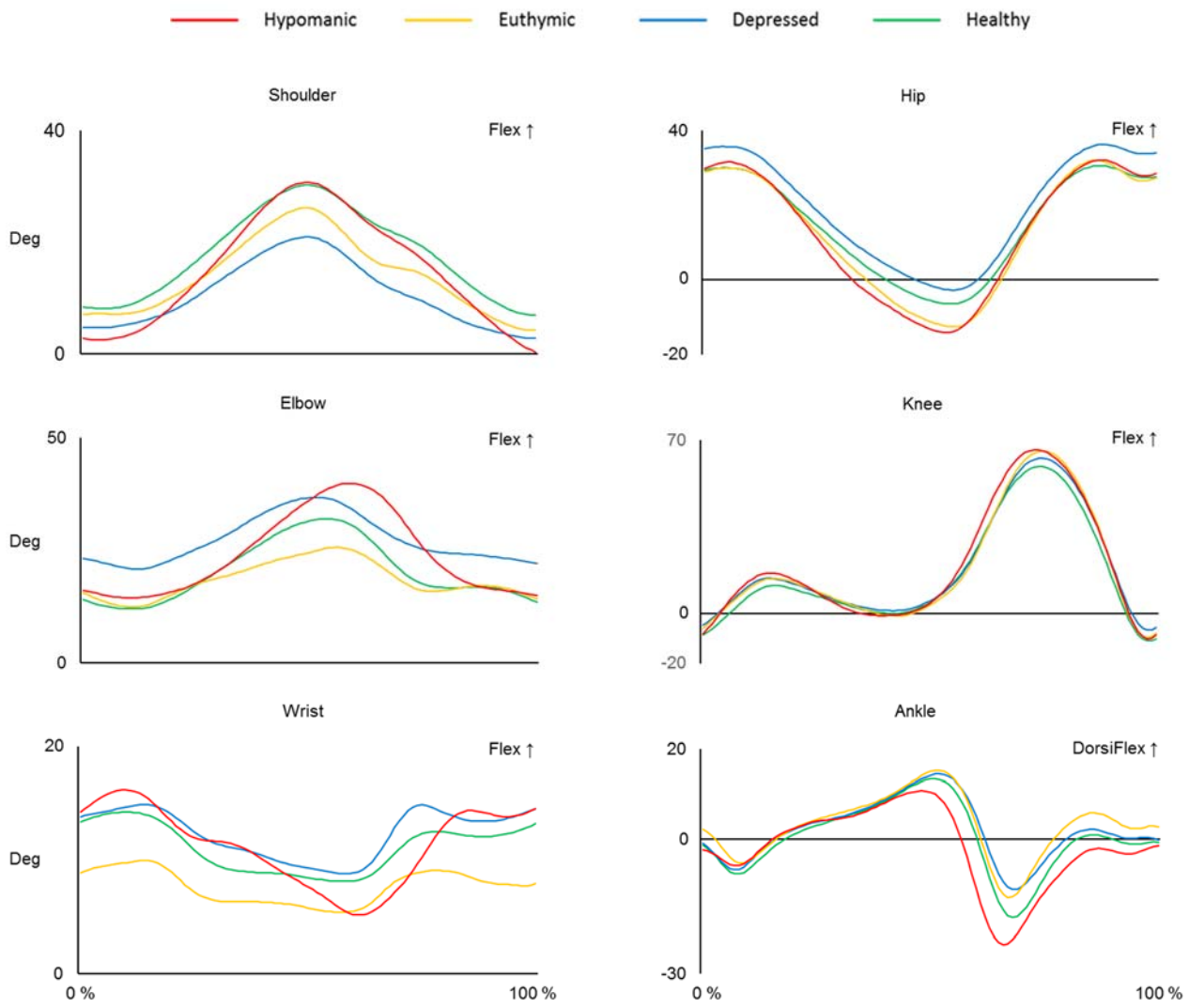

Fig. 4.7. Mean joint angles in the sagittal plane for each group for the upper (left column) and lower (right column) extremity during one gait cycle for the comfortable speed condition.

Table 4.5
Mean ranges of motion in the sagittal plane at the shoulder, elbow, wrist, hip, knee and ankle for each speed condition and group

	Hypomanic	Euthymic	Depressed	Healthy
Slow				
Shoulder (deg)	16.1 (7.7)	13.0 (3. 9)	11.6 (5.7)	15.9 (5.1)
Elbow (deg)	13.3 (5.2)	10.5 (2.7)	11.1 (2.3)	15.0 (7.4)
Wrist (deg)	6.1 (1.5)	5.5 (2.2)	5.8 (2.2)	4.9 (1.8)
Hip (deg)	40.8 (3.8)^{HC*}	38.9 (4.5)^{HC*}	35.2 (6.3)	32.8 (3.0)^{HM*,EU*}
Knee (deg)	71.7 (4.0)	68.8 (8.4)	65.4 (7.4)	66.2 (4.5)
Ankle (deg)	32.9 (7.1)	23.9 (3.0)	27.2 (6.5)	29.6 (5.3)
Comfortable				
Shoulder	31.3 (20.5)	22.4 (11.0)	18.8 (5.4)	24.3 (7.7)
Elbow	28.8 (10.0)	16.2 (11.1)	17.6 (8.1)	21.5 (10.8)
Wrist	13.7 (2.3)^{HC*,EU*}	7.3 (4.4)^{HM*}	8.8 (4.1)	8.1 (2.6)^{HM*}
Hip	47.6 (2.9)^{HC**,DP*}	45.4 (5.1)^{HC**}	40.5 (5.0)^{HM*}	38.6 (3.1)^{HM**,EU**}
Knee	76.4 (6.7)	75.8 (7.2)	70.4 (6.1)	70.9 (5.0)
Ankle	35.5 (4.6)	29.0 (2.7)	28.3 (4.8)	32.0 (5.7)
Fast				
Shoulder	31.2 (21.4)	35.0 (21.2)	34.0 (13.9)	36.1 (9.3)
Elbow	35.7 (23.8)	25.7 (13.3)	36.0 (12.5)	36.8 (13.2)
Wrist	17.2 (6.4)	10.0 (5.3)	14.4 (9.0)	11.4 (3.5)
Hip	53.1 (3.9)	55.1 (5.9)	53.5 (8.6)	48.5 (5.3)
Knee	70.2 (7.9)	73.2 (5.1)	71.8 (6.1)	69.6 (4.8)
Ankle	35.8 (1.6)	31.4 (3.0)	30.7 (4.4)	32.1 (6.2)

Note: Values in parentheses are standard deviations. Superscript letters are significant differences between groups based on multiple comparisons using one-way ANOVA with Tukey post-hoc analysis: HM=Hypomanic, EU=Euthymic, DP=Depressed, HC=Healthy. * $p < .05$. ** $p < .01$.

Table 4.6

Estimates and 95% confidence intervals for sagittal ranges of motion based on the linear mixed model

	Gait speed	Healthy vs. Hypomanic	Euthymic vs. Hypomanic	Depressed vs. Hypomanic	Healthy vs. Euthymic	Depressed vs. Euthymic	Healthy vs. Depressed
Slow							
Shoulder	**12.12***** **(6.32, 17.92)**	3.01 (-2.76, 8.78)	-0.11 (-6.42, 6.21)	-1.36 (-7.35, 4.64)	3.12 (-1.43, 7.66)	-1.25 (-6.09, 3.59)	**4.37*** **(0.30, 8.43)**
Elbow	**6.65*** **(1.04, 12.27)**	3.45 (-3.10, 10.00)	-1.08 (-8.27, 6.12)	-0.48 (-7.29, 6.34)	4.53 (-0.69, 9.75)	0.60 (-4.95, 6.15)	3.93 (-0.74, 8.60)
Wrist	2.27 (-0.30, 4.85)	-0.61 (-2.92, 1.17)	0.02 (-2.51, 2.55)	0.32 (-2.09, 2.72)	-0.63 (-2.44, 1.18)	0.30 (-1.63, 2.22)	-0.93 (-2.55, 0.69)
Hip	**8.06***** **(4.91, 11.21)**	**-5.90*** **(-10.69, -1.11)**	0.11 (-5.16, 5.39)	-3.51 (-8.49, 1.48)	**-6.01*** **(-9.87, -2.16)**	-3.62 (-7.72, -0.48)	-2.39 (-5.84, 1.05)
Knee	**16.37***** **(11.87, 20.87)**	-1.18 (-6.80, 4.43)	1.22 (-4.95, 7.39)	-2.09 (-7.94, 3.75)	-2.40 (-6.89, 2.08)	-3.31 (-8.09, 1.46)	0.91 (-3.10, 4.92)
Ankle	**7.43**** **(2.15, 12.70)**	-1.42 (-7.90, 5.06)	-7.17* (-14.30, -0.05)	-3.84 (-10.59, 2.90)	**5.76*** **(0.58, 10.93)**	3.33 (-2.18, 8.84)	2.43 (-2.20, 7.05)
Comfortable							
Shoulder	0.89 (-9.91, 11.67)	-6.73 (-18.71, 5.25)	-8.61 (-21.76, 4.55)	-12.14 (-24.81, 0.52)	1.88 (-7.47, 11.22)	-3.54 (-13.51, 6.43)	5.41 (-2.97, 13.80)
Elbow	6.62 (-4.51, 17.76)	-4.99 (-16.76, 6.78)	-10.25 (-23.16, 2.67)	-8.46 (-20.92, 4.01)	5.26 (-3.87, 14.39)	1.79 (-7.95, 11.53)	3.47 (-4.73, 11.67)
Wrist	2.78 (-2.31, 7.87)	**-4.61*** **(-8.84, -0.38)**	**-5.37*** **(-9.98, -0.75)**	-3.71 (-8.23, 0.81)	0.76 (-2.40, 3.92)	1.65 (-1.73, 5.03)	-0.89 (-3.74, 1.95)
Hip	**13.46***** **(9.80, 17.11)**	**-4.49*** **(-8.75, -0.23)**	0.302 (-7.09, 2.27)	-1.73 (-6.23, 2.77)	**-6.90***** **(-10.24, -3.57)**	**-4.15*** **(-7.70, -0.59)**	-2.76 (-5.75, 0.24)
Knee	**4.85*** **(0.59, 9.11)**	-3.90 (-10.71, 2.91)	1.08 (-6.43, 8.59)	-4.07 (-11.22, 3.08)	-4.98 (-10.42, 0.47)	-5.15 (-10.95, 0.65)	0.17 (-4.71, 5.05)
Ankle	0.22 (-5.24, 5.69)	-3.45 (-9.38, 2.48)	-6.48 (-12.99, 0.03)	**-7.18*** **(-0.90, -13.45)**	3.03 (-1.59, 7.64)	-0.70 (-5.62, 4.22)	3.73 (-0.41, 7.87)
Fast							
Shoulder	**20.13***** **(11.12, 29.15)**	8.86 (-24.50, 6.78)	10.29 (-7.12, 27.71)	7.75 (-8.61, 24.11)	-1.43 (-14.17, 11.31)	-2.54 (-16.07, 10.99)	1.11 (-10.25, 12.47)
Elbow	**28.80***** **(18.04, 39.57)**	6.67 (-9.07, 22.42)	-0.73 (-18.32, 16.86)	7.33 (-9.16, 23.82)	7.40 (-5.41, 20.22)	8.06 (-5.54, 21.65)	-0.66 (-12.07, 10.76)
Wrist	3.84 (-1.71, 9.39)	-5.07 (-12.25, 2.11)	-5.95 (-14.00, 2.09)	-1.92 (-9.44, 5.61)	0.88 (-4.96, 6.72)	4.04 (-2.15, 10.22)	-3.15 (-8.35, 2.04)
Hip	**14.75***** **(11.71, 17.79)**	-1.68 (-7.42, 4.06)	**6.79*** **(0.40, 13.17)**	4.00 (-2.00, 10.00)	**-8.47*** **(-13.14, -3.79)**	-2.79 (-7.76, 2.18)	**-5.68*** **(-9.85, -1.51)**
Knee	1.48 (-2.74, 5.71)	-0.30 (-6.78, 6.18)	3.49 (-3.74, 10.73)	1.97 (-4.82, 8.75)	-3.80 (-9.07, 1.48)	-1.53 (-7.13, 4.07)	-2.27 (-6.97, 2.43)
Ankle	3.23 (-1.10, 7.56)	-3.08 (-9.05, 2.89)	-3.36 (-10.03, 3.32)	-4.28 (-10.54, 1.97)	0.28 (-4.58, 5.14)	-0.92 (-6.07, 4.22)	1.20 (-3.12, 5.53)

Note: Values in parentheses are lower and upper bounds for 95% confidence intervals. Bold fonts with asterisks indicate significant differences between groups. * $p < .05$. ** $p < .01$. *** $p < .001$.

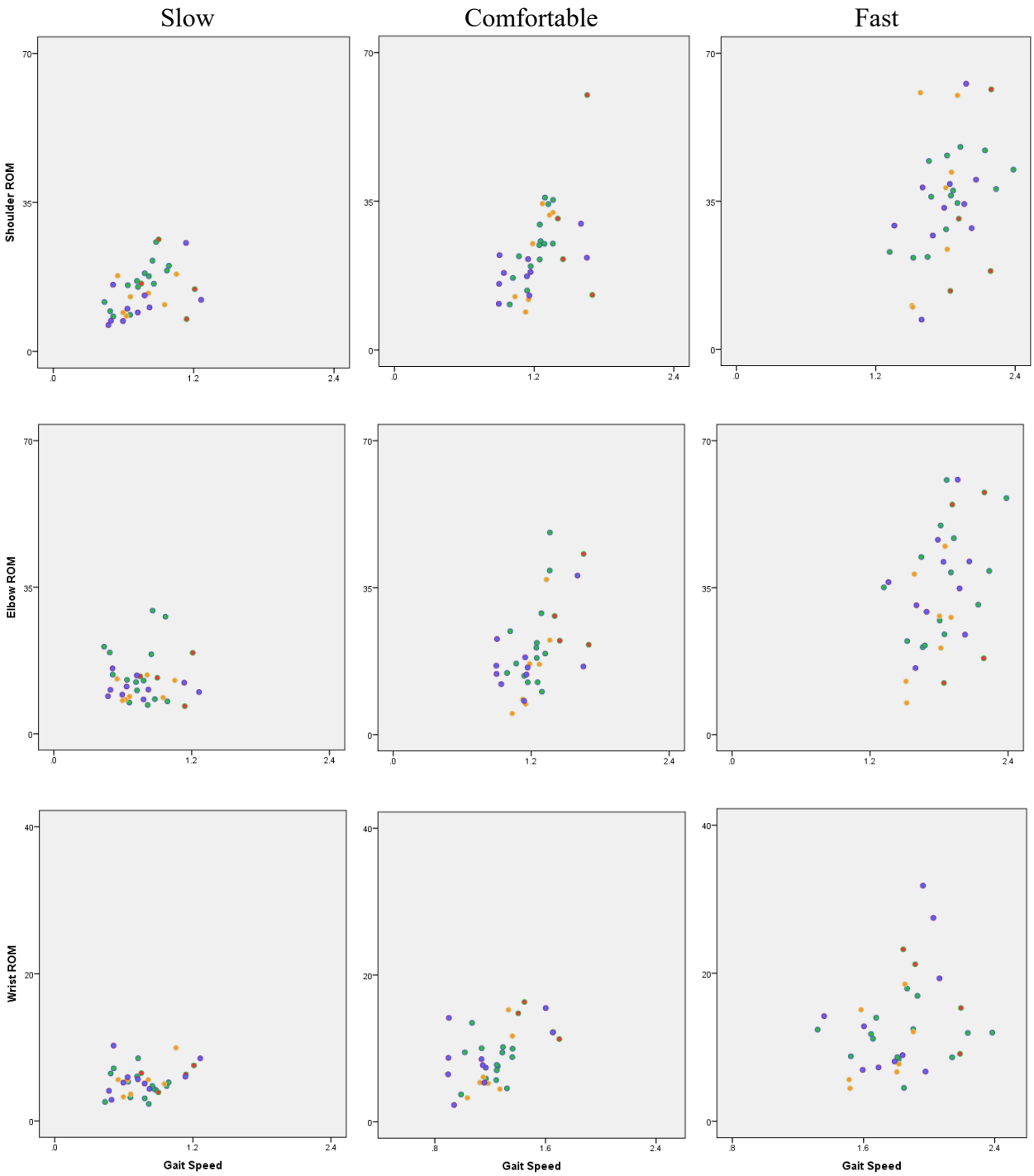

Fig. 4.8. The relationships between gait speed and sagittal ranges of motion (ROM) at the shoulder (top row), elbow (middle row) and wrist (bottom row) for the slow (left column), comfortable (middle column) and fast speed (right column) conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group, blue for the depressed group and green for healthy controls.

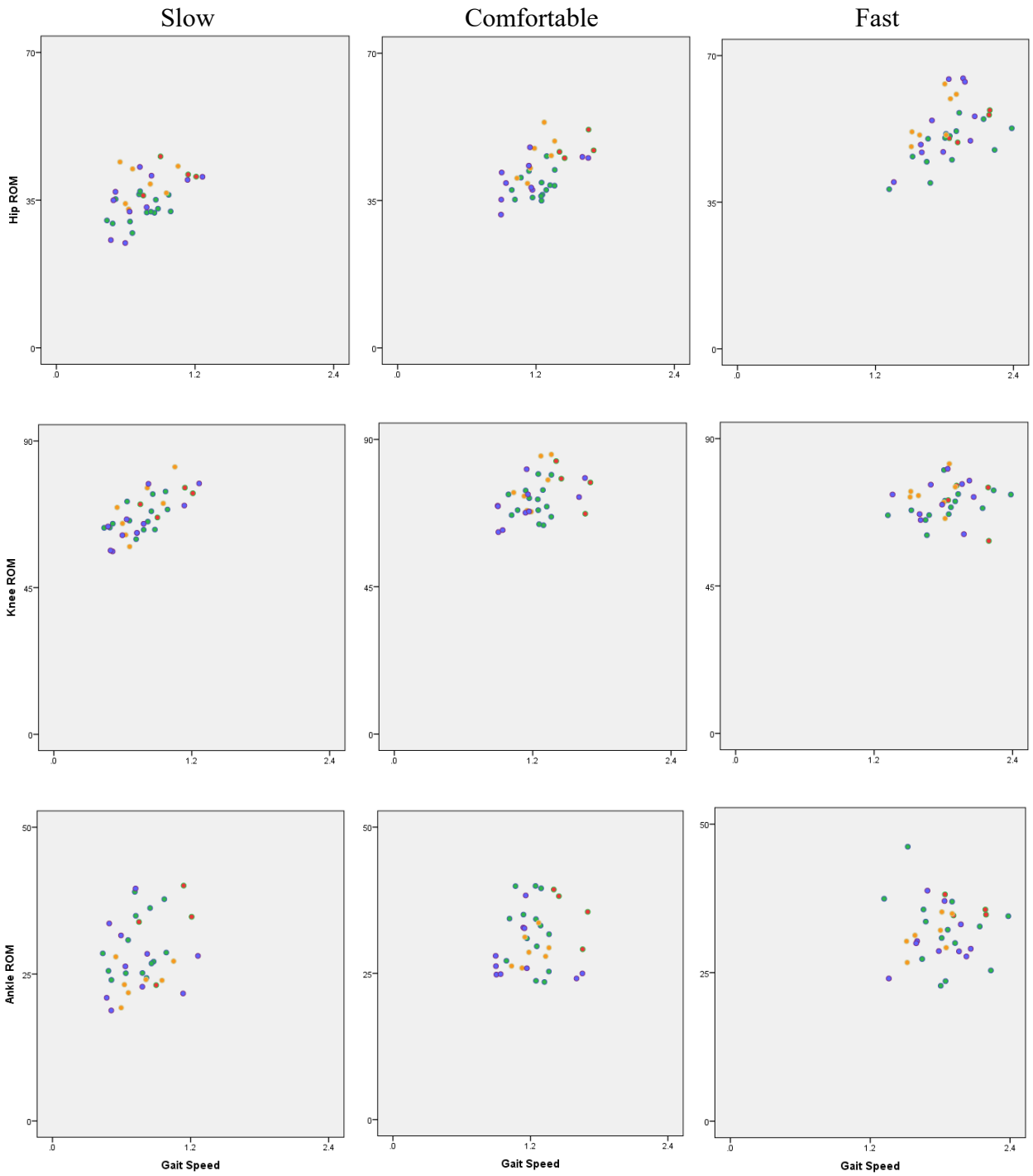

Fig. 4.9. The relationships between gait speed and sagittal ranges of motion (ROM) in the hip (top row), knee (middle row) and ankle (bottom row) for the slow (left column), comfortable (middle column) and fast speed (right column) conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group, blue for the depressed group and green for healthy controls.

4.4.3.2 Upper body posture

Mean angles in the sagittal plane for the head and thorax during one gait cycle are shown for the comfortable speed condition in Fig. 4.10. Mean head angle differed between groups for the comfortable and slow speed conditions (Table 4.9). For the comfortable speed condition, head posture was 9.9° more flexed for the euthymic group than for the depressed group ($p < 0.05$). For the slow speed condition, head posture was 9.8° and 8.1° more flexed for the euthymic group than for the depressed group and healthy controls, respectively (all $p < 0.05$). There were no significant differences in mean thorax angle between groups for any speed condition.

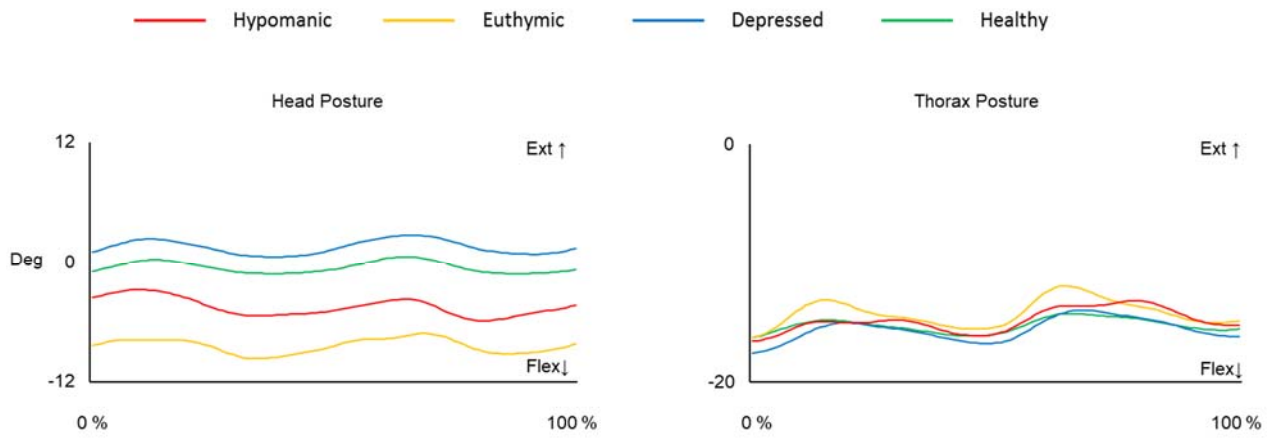

Fig. 4.10. Mean angles in the sagittal plane for each group for head (left) and thorax (right) during one gait cycle for the comfortable speed condition.

The relationships between gait speed and upper body posture for each speed condition are shown in Fig. 4.11. Head posture was independent of gait speed for all speed conditions (all $p > 0.05$) but thorax flexion increased with gait speed for all speed conditions (all $p < 0.05$) (Table 4.10). When the effect of gait speed and groups were isolated using the linear mixed model, head posture was more flexed for the euthymic group than for the depressed group and healthy controls

for the comfortable (all $p < 0.05$; $d = 1.5$ and 1.4, respectively) and slow speed conditions (all $p < 0.05$; $d = 1.6$ and 1.2, respectively) (Table 4.10). In contrast, thorax posture did not depend on group but flexion tended to increase with gait speed for all speed conditions (all $p < 0.05$) (Table 4.10).

Table 4.7
Mean head and thorax angles in the sagittal plane for each speed condition and group

	Hypomanic	Euthymic	Depressed	Healthy
Slow				
Head (deg)	-2.1 (3.5)	-8.1 (5.9)^{HC*,DP*}	1.7 (6.0)^{EU*}	0.0 (6.5)^{EU*}
Thorax (deg)	-14.0 (10.1)	-13.2 (3.6)	-14.6 (5.0)	-14.4 (8.9)
Comfortable				
Head	-4.5 (6.0)	-8.4 (8.9)^{DP*}	1.5 (6.5)^{EU*}	-0.5 (6.5)
Thorax	-14.8 (10.0)	-14.2 (3.6)	-15.6 (5.1)	-15.2 (9.3)
Fast				
Head	1.0 (4.2)	-5.2 (6.0)	1.9 (8.4)	-2.5 (7.8)
Thorax	-15.1 (10.4)	-14.3 (3.6)	-18.2 (6.6)	-16.9 (11.8)

Note: Positive values indicate extension. Values in parentheses are standard deviations. Superscript letters are significant differences between groups based on multiple comparisons using one-way ANOVA with Tukey post-hoc analysis. HM=Hypomanic, EU=Euthymic, DP=Depressed, HC=Healthy. * $p < .05$.

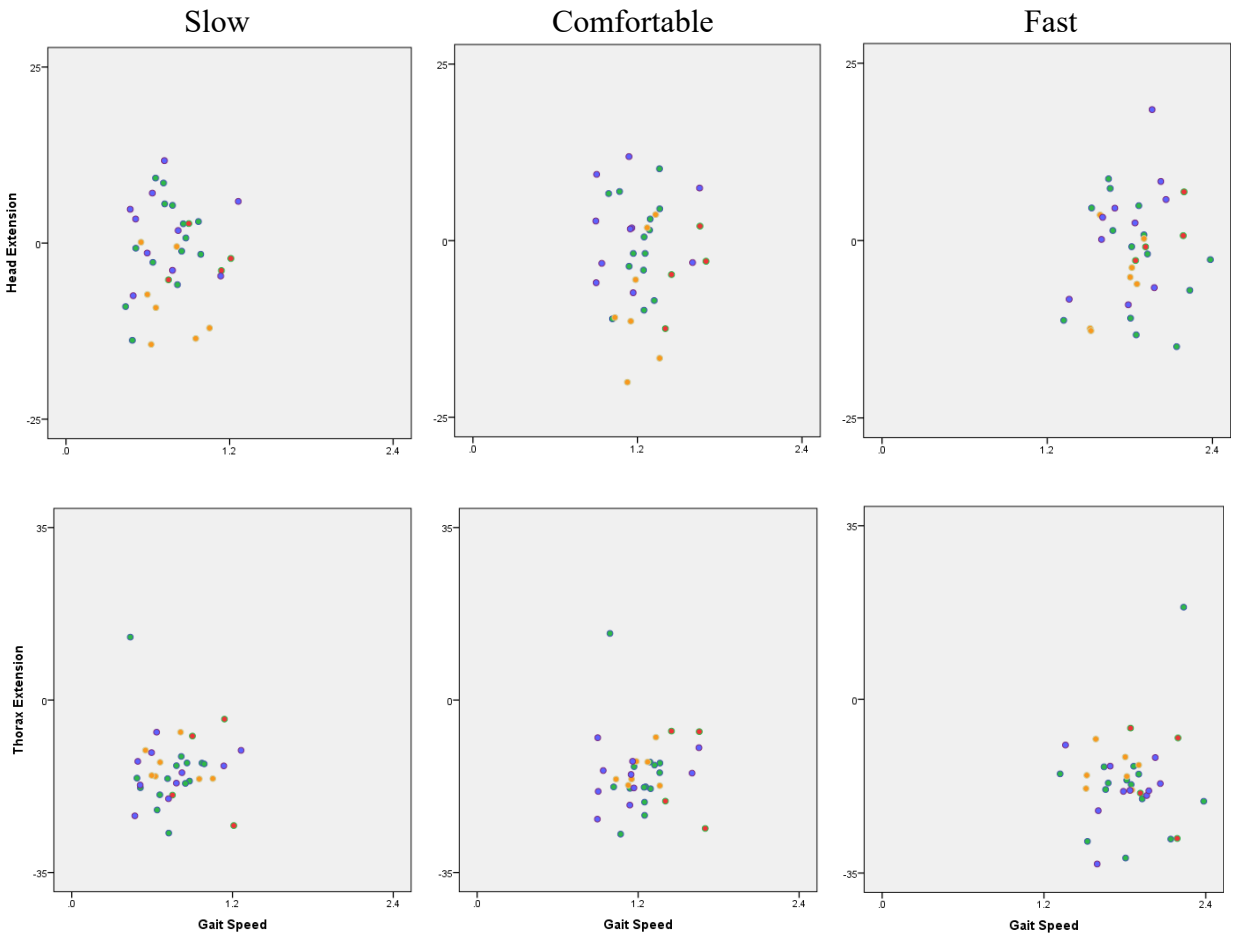

Fig. 4.11. The relationships between gait speed and head extension (top row), and thorax extension (bottom row) for the slow (left column), comfortable (middle column) and fast speed (right column) conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group, blue for the depressed group and green for healthy controls.

Table 4.8
Estimates and 95% confidence intervals for head and thorax angles in the sagittal plane based on the linear mixed model

	Gait speed	Healthy vs. Hypomanic	Euthymic vs. Hypomanic	Depressed vs. Hypomanic	Healthy vs. Euthymic	Depressed vs. Euthymic	Healthy vs. Depressed
Slow							
Head	-2.09 (-9.24, 5.07)	1.60 (-5.74, 8.95)	-6.51 (-14.56, 1.54)	3.33 (-4.31, 10.96)	**8.11**** **(2.31, 13.92)**	**9.84**** **(3.66, 16.01)**	-1.72 (-6.91, 3.47)
Thorax	**-3.25**** **(-5.46, -1.04)**	-1.30 (-9.73, 7.12)	0.01 (-9.30, 9.32)	-1.41 (-10.20, 7.38)	-1.32 (-8.18, 5.55)	-1.43 (-8.74, 5.88)	0.11 (-6.03, 6.25)
Comfortable							
Head	6.04 (-4.54, 16.63)	6.03 (-2.78, 14.85)	-1.83 (-11.45, 7.80)	8.49 (-0.93, 17.91)	**7.86*** **(1.27, 14.45)**	**10.31**** **(3.27, 17.36)**	-2.45 (-8.39, 3.48)
Thorax	**-3.71*** **(-6.62, -0.81)**	-1.68 (-10.41, 7.04)	-0.65 (-10.29, 8.99)	-2.26 (-11.38, 6.86)	-1.04 (-8.12, 6.05)	-1.61 (-9.16, 5.93)	0.58 (-5.76, 6.92)
Fast							
Head	-2.36 (-8.95, 4.23)	-3.94 (-12.75, 4.88)	-6.92 (-16.79, 2.95)	0.37 (-8.87, 9.61)	2.98 (-4.19, 10.16)	7.29 (-0.32, 14.89)	-4.30 (-10.69, 2.08)
Thorax	**-5.83***** **(-7.95, -3.71)**	-2.91 (-13.86, 8.04)	-1.03 (-13.15, 11.09)	-4.47 (-15.90, 6.96)	-1.88 (-10.82, 7.07)	-3.44 (-12.96, 6.08)	1.56 (-6.43, 9.56)

Note: Values in parentheses are lower and upper bounds for 95% confidence intervals. Bold fonts with asterisks indicate significant differences between groups. * $p < .05$. ** $p < .01$. *** $p < .001$.

4.4.3.3 Center-of-mass displacement and smoothness

Mean center-of-mass displacement and smoothness in the anteroposterior, vertical and mediolateral directions during one gait cycle are shown for the comfortable speed condition in Fig. 4.12. Anteroposterior and vertical center-of-mass displacements were significantly different between groups only for the comfortable speed condition (Table 4.11). Anteroposterior center-of-mass displacement was 20.8 and 17.2% greater for the hypomanic group than for the depressed group and healthy controls, respectively, for the comfortable speed condition (all $p < 0.05$; $d = 1.5$ and 2.1, respectively). Vertical center-of-mass displacement was 25.4 and 21.3% less for healthy controls than for the hypomanic group and the euthymic group for the comfortable speed condition

(all $p < 0.05$; $d = 1.5$ and 1.0, respectively). Mediolateral center-of-mass displacement was similar across groups for all speed conditions.

Significant differences in center-of-mass smoothness were found in the mediolateral direction between the depressed group and healthy controls for the comfortable speed condition, but center-of-mass smoothness was not significantly different between groups in the anteroposterior and vertical directions for any speed condition (Table 4.11). Mediolateral normalized jerk score was 29.6% less for healthy controls than for the depressed group for the comfortable speed condition ($p < 0.05$; $d = 0.3$), indicating smoother center-of-mass movement in the mediolateral direction for the depressed group. Anteroposterior and vertical normalized jerk scores were not difference between groups.

The relationship between gait speed, and center-of-mass displacement and smoothness for each speed condition are shown in Fig. 4.13 and Fig. 4.14, respectively. Anteroposterior center-of-mass displacement, and anteroposterior and vertical normalized jerk scores depended on gait speed for all speed conditions (all $p < 0.05$) (Table 4.12). Vertical center-of-mass displacement depended on gait speed for the comfortable and slow speed conditions, and mediolateral center-of-mass displacement and normalized jerk score depended on gait speed for the slow speed condition (all $p < 0.05$) (Table 4.12). Vertical center-of-mass displacement for the fast speed condition, and mediolateral center-of-mass displacement and normalized jerk score in the mediolateral direction for the comfortable and fast speed conditions were independent of gait speed (all $p > 0.05$) (Table 4.12). After accounting for the effect of gait speed, anteroposterior and vertical center-of-mass displacements were greater for the euthymic group than for the depressed group and healthy controls for the comfortable (all $p < 0.05$; $d = 0.8$ and 0.9, respectively, for the anteroposterior direction; $d = 1.0$ and 1.6, respectively, for the vertical direction) and slow speed

conditions (all $p < 0.05$; $d = 0.5$ and 0.6, respectively, for the anteroposterior direction; $d = 0.59$ and 1.4, respectively, for the vertical direction), and greater for the euthymic group than for healthy controls for the fast speed condition (all $p < 0.05$; $d = 0.4$ for the anteroposterior direction; $d = 0.9$ for the vertical direction). Anteroposterior normalized jerk score was less for the depressed group than for the hypomanic group and the euthymic group for the comfortable speed condition (all $p < 0.05$; $d = 0.4$ and 1.2, respectively), and greater for the depressed group than for the hypomanic group for the slow speed condition ($p < 0.05$; $d = 0.2$). In addition, mediolateral normalized jerk score was less for healthy controls than for the depressed group for the comfortable speed condition ($p < 0.05$).

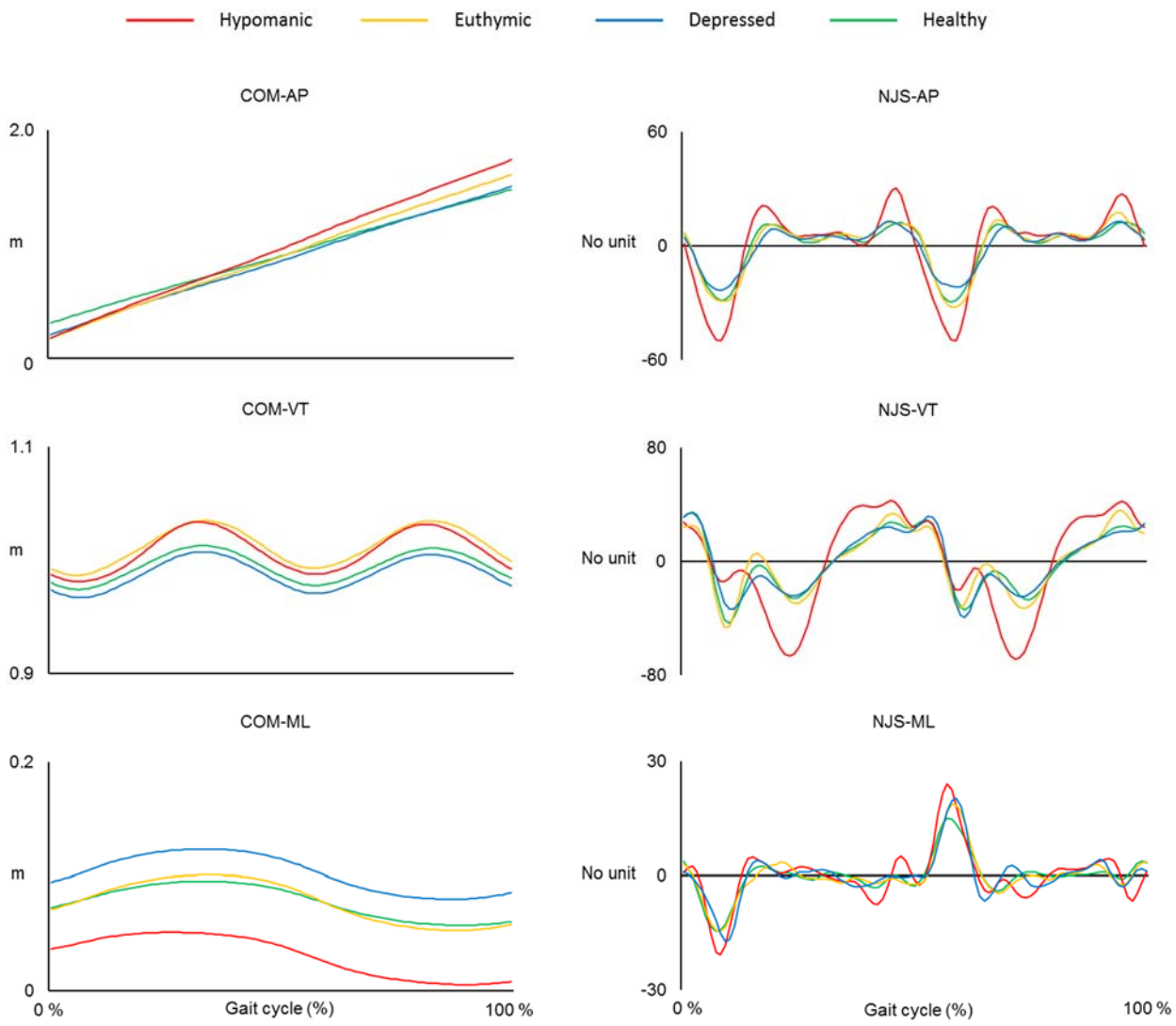

Fig. 4.12. Mean center-of-mass displacements (COM, left column) and normalized jerk scores (NJS, right column) for each group in the anteroposterior (AP, top row), vertical (VT, middle row) and mediolateral (ML, bottom row) directions during one gait cycle for the comfortable speed condition.

Table 4.9

Mean values for center-of-mass (COM) displacement and normalized jerk scores (NJS) in the anteroposterior (AP), vertical (VT) and mediolateral (ML) directions for each speed condition and group

	Hypomanic	Euthymic	Depressed	Healthy
Slow				
COM-AP (m)	1.29 (0.11)	1.17 (0.15)	1.08 (0.21)	1.09 (0.14)
COM-VT (cm)	3.86 (0.90)	3.37 (0.85)	2.78 (1.00)	2.66 (0.52)
COM-ML (cm)	7.50 (2.46)	7.16 (2.07)	7.06 (1.39)	6.94 (1.67)
NJS-AP (no unit)	152.5 (34.0)	177.5 (33.4)	160.0 (56.7)	181.3 (54.5)
NJS-VT (no unit)	10183.5 (3908.6)	14322.3 (5576.3)	15102.3 (8234.7)	14508.3 (6292.7)
NJS-ML (no unit)	1623.3 (731.7)	2082.7 (723.7)	1977.5 (707.2)	1729.7 (235.8)
Comfortable				
COM-AP	1.57 (0.04)^{HC*,DP**}	1.44 (0.10)	1.30 (0.18)^{HM**}	1.34 (0.11)^{HM*}
COM-VT	5.40 (0.92)^{HC*}	5.12 (1.08)^{HC*}	4.19 (0.90)	4.03 (0.68)^{HM*,EU*}
COM-ML	4.95 (1.11)	5.55 (1.39)	4.88 (1.01)	5.51 (1.33)
NJS-AP	121.1 (29.9)	130.6 (18.7)	108.9 (20.4)	114.6 (15.2)
NJS-VT	5754.5 (567.1)	6520.9 (845.2)	6894.4 (1154.3)	6505.4 (1310.8)
NJS-ML	1724.1 (815.6)	1889.9 (406.0)	2136.2 (680.0)^{HC*}	1503.3 (343.6)^{DP*}
Fast				
COM-AP	1.78 (0.05)	1.71 (0.12)	1.65 (0.17)	1.63 (0.19)
COM-VT	6.55 (0.87)	6.85 (1.21)	6.31 (1.39)	5.40 (1.60)
COM-ML	4.25 (1.54)	4.37 (1.12)	4.58 (2.14)	3.93 (1.44)
NJS-AP	94.4 (22.4)	122.0 (24.8)	97.9 (19.0)	96.2 (24.8)
NJS-VT	5376.4 (620.6)	5330.1 (538.6)	5305.0 (396.9)	5363.9 (420.0)
NJS-ML	1978.9 (1347.4)	2274.6 (762.7)	2293.8 (907.7)	1853.3 (530.6)

Note: Values in parentheses are standard deviations. Superscript letters are significant differences between groups based on multiple comparisons using one-way ANOVA with Tukey post-hoc analysis: HM=Hypomanic, EU=Euthymic, DP=Depressed, HC=Healthy. * $p < .05$. ** $p < .01$.

Table 4.10

Estimates and 95% confidence intervals for center-of-mass (COM) displacement and normalized jerk scores (NJS) in the anteroposterior (AP), vertical (VT) and mediolateral (ML) directions based on the linear mixed model

	Gait speed	Healthy vs. Hypomanic	Euthymic vs. Hypomanic	Depressed vs. Hypomanic	Healthy vs. Euthymic	Depressed vs. Euthymic	Healthy vs. Depressed
Slow							
COM-AP	**0.63***** **(0.57, 0.70)**	-0.03 (-0.12, 0.06)	0.040 (-0.05, 0.13)	-0.05 (-0.14, 0.04)	**-0.07*** **(-0.14, 0.00)**	**-0.09*** **(-0.16, -0.02)**	0.02 (-0.04, 0.08)
COM-VT	**0.03***** **(0.02, 0.03)**	-0.01 (-0.01, 0.00)	0.001 (0.00, 0.01)	-0.004 (-0.01, 0.00)	**-0.01**** **(-0.01, 0.00)**	**-0.01*** **(-0.01, 0.00)**	-0.001 (-0.01, 0.00)
COM-ML	**-0.04**** **(-0.06, -0.02)**	-0.02 (-0.03, 0.00)	-0.01 (-0.03, 0.01)	-0.01 (-0.03, 0.01)	-0.003 (-0.02, 0.01)	-0.001 (-0.02, 0.01)	-0.001 (-0.01, 0.01)
NJS-AP	**-236***** **(-277, -196)**	-34 (-76, 9)	-34 (-81, 12)	**-53*** **(-97, -9)**	0.74 (-33, 34)	-19 (-55, 16)	20 (-10, 50)
NJS-VT	**-25290***** **(-30448, -20132)**	-2340 (-7196, 2517)	-2200 (-7515, 3115)	-1597 (-6640, 3447)	-140 (-3950, 3670)	603 (-3453, 4659)	-743 (-4151, 2665)
NJS-ML	**-923*** **(-1705, -140)**	-137 (-801, 528)	228 (-497, 953)	117 (-573, 806)	-365 (-881, 151)	-112 (-661, 438)	-253 (-715, 208)
Comfortable							
COM-AP	**0.56***** **(0.49, 0.62)**	-0.03 (-0.12, 0.05)	0.06 (-0.03, 0.16)	-0.04 (-0.13, 0.05)	**-0.10**** **(-0.17, -0.03)**	**-0.11**** **(-0.18, -0.03)**	0.01 (-0.05, 0.07)
COM-VT	**0.03***** **(0.02, 0.04)**	-0.003 (-0.01, 0.01)	0.008 (0.00, 0.02)	0.001 (-0.01, 0.01)	**-0.01**** **(-0.02, 0.00)**	-0.01 (-0.01, 0.00)	-0.003 (-0.01, 0.00)
COM-ML	-0.004 (-0.03, 0.02)	0.004 (-0.01, 0.02)	0.005 (-0.01, 0.02)	-0.002 (-0.02, 0.02)	-0.0004 (-0.01, 0.01)	-0.01 (-0.02, 0.01)	0.01 (0.00, 0.02)
NJS-AP	**-33**** **(-52, -13)**	-17 (-40, 5)	-2 (-27, 23)	**-25*** **(-49, -23)**	-16 (-33, 2)	**-24*** **(-42, -5)**	8 (-8, 24)
NJS-VT	**-4150***** **(-5521, -2780)**	-648 (-1787, 492)	-655 (-1899, 588)	-525 (-1743, 692)	8 (-844, 860)	130 (-780, 1040)	-122 (-889, 645)
NJS-ML	-537 (-1509, 434)	-402 (-1092, 288)	-18 (-768, 731)	197 (-547, 941)	-384 (-880, 112)	215 (-316, 746)	**-598*** **(-1046, -150)**
Fast							
COM-AP	**0.36***** **(0.30, 0.42)**	-0.08 (-0.22, 0.06)	0.05 (-0.10, 0.21)	-0.03 (-0.18, 0.11)	**-0.13*** **(-0.24, -0.02)**	-0.09 (-0.21, 0.04)	-0.04 (-0.15, 0.06)
COM-VT	-0.003 (-0.01, 0.01)	-0.01 (-0.03, 0.00)	0.002 (-0.02, 0.02)	-0.003 (-0.02, 0.01)	**-0.01*** **(-0.03, 0.00)**	-0.01 (-0.02, 0.01)	-0.01 (-0.02, 0.00)
COM-ML	-0.01 (-0.04, 0.01)	-0.01 (-0.03, 0.01)	-0.003 (-0.03, 0.02)	-0.0003 (-0.02, 0.02)	-0.003 (-0.02, 0.01)	0.003 (-0.01, 0.02)	-0.01 (-0.02, 0.01)
NJS-AP	**-37***** **(-48, -26)**	-6 (-32, 21)	16 (-14, 45)	-6 (-33, 22)	-21 (-43, 0)	-21 (-44, 2)	0.07 (-19, 19)
NJS-VT	**-612*** **(-1115, -111)**	-132 (-644, 379)	-244 (-822, 334)	-221 (-759, 317)	111 (-304, 526)	23 (-416, 461)	89 (-279, 456)
NJS-ML	338 (-685, 1360)	-59 (-1021, 902)	405 (-686, 1495)	397 (-616, 1410)	-464 (-1243, 315)	-7 (-829, 815)	-457 (-1146, 232)

Note: Values in parentheses are lower and upper bounds for 95% confidence intervals. Bold fonts with asterisks indicate significant differences between groups. * $p < .05$. ** $p < .01$. *** $p < .001$.

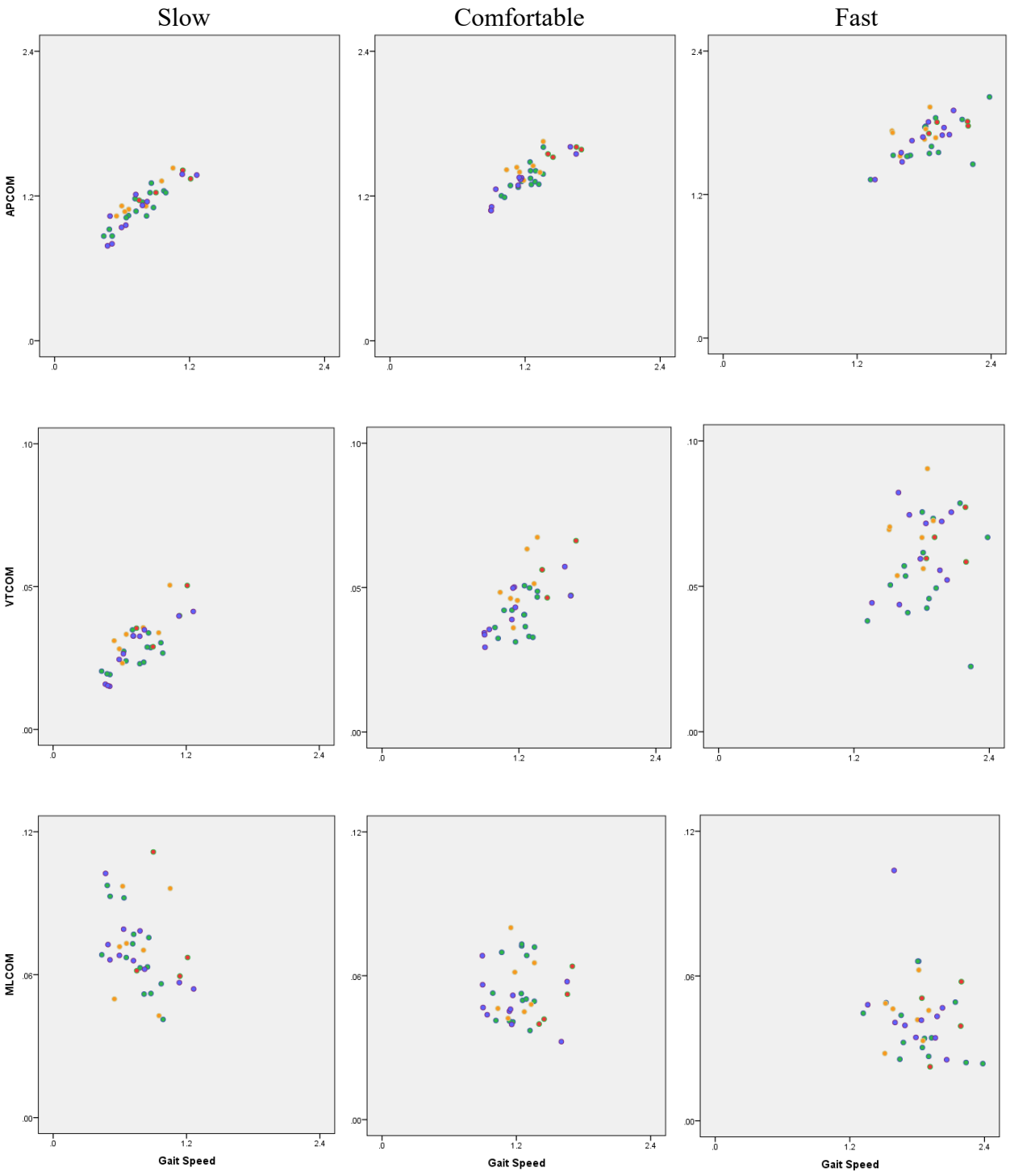

Fig. 4.13. The relationships between gait speed and center-of-mass (COM) displacement in the anteroposterior (AP, top row), vertical (VT, middle row), and mediolateral (ML, bottom row) directions for the slow (left column), comfortable (middle column) and fast speed (right column) conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group, blue for the depressed and green for healthy controls.

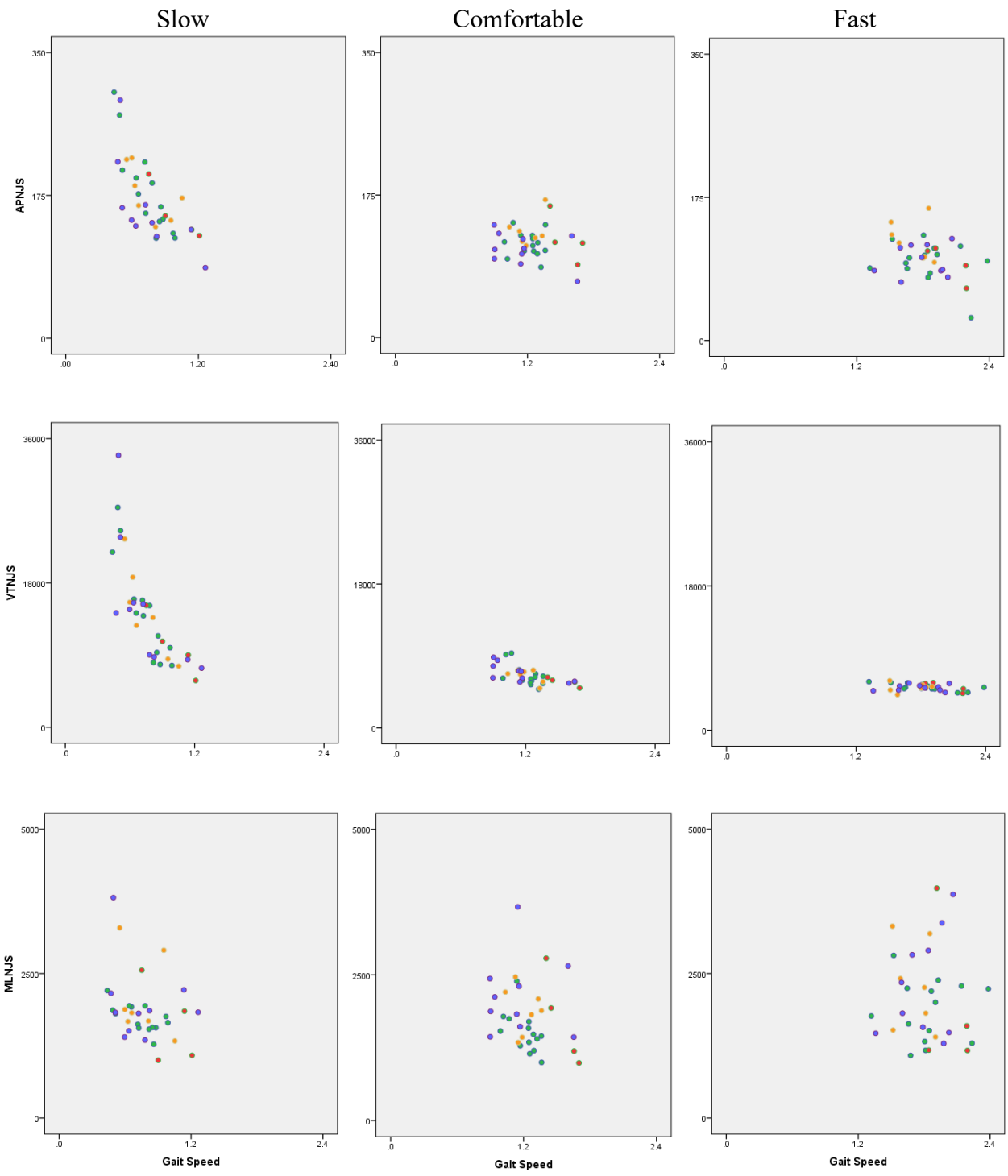

Fig. 4.14. The relationships between gait speed and normalized jerk scores (NJS) in the anteroposterior (AP, top row), vertical (VT, middle row), and mediolateral (ML, bottom row) directions for the slow (left column), comfortable (middle column) and fast speed (right column) conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group, blue for the depressed group and green for healthy controls.

4.4.4 Kinetic gait analysis

One individual in the euthymic group was excluded from the kinetic gait analysis due to a technical issue. In addition, the slow speed condition for one individual in the depressed group was excluded because ground reaction force data were not available. As a result, four hypomanic individuals, six euthymic individuals, ten depressed individuals and fourteen healthy controls were included in the kinetic gait analysis.

4.4.4.1 Peak ground reaction forces

Mean ground reaction forces in the anteroposterior and vertical directions for each group during stance phase are shown for the comfortable speed condition in Fig. 4.15. Across all speed conditions, the positive and negative peaks in the anteroposterior ground reaction forces, and the 1st peak in the vertical ground reaction forces tended to be greater for the hypomanic group than for the other groups (Table 4.13). The positive peak in the anteroposterior ground reaction forces was 44.4 and 36.8% greater for the hypomanic group than for the depressed group and healthy controls, respectively (all $p < 0.05$; $d = 1.6$ and 2.3, respectively), for the comfortable speed condition, and 41.7% greater for the hypomanic group than for healthy controls for the slow speed condition ($p < 0.05$; $d = 1.7$). The negative peak in the anteroposterior ground reaction forces was 50.0, 58.8 and 50.0% greater for the hypomanic group than for the euthymic group, the depressed group and healthy controls, respectively, for the comfortable speed condition (all $p < 0.05$; $d = 3.0$, 2.0 and 3.0, respectively).

For the vertical ground reaction forces, significant differences between groups were found in the 1st peak and valley for the comfortable and slow speed conditions (Table 4.13). The 1st peak was 18.3, 19.4 and 20.6% greater for the hypomanic group than for the euthymic group, the depressed group and healthy controls, respectively, for the comfortable speed condition (all $p < 0.05$; $d = 2.9$, 2.1 and 3.7, respectively), and 6.0% greater for the hypomanic group than for the depressed group for the slow speed condition ($p < 0.05$). The valley was 23.3, 25.3 and 27.3% less for the hypomanic group than for the euthymic group, the depressed group and healthy controls, respectively, for the comfortable speed condition (all $p < 0.05$; $d = 2.4$, 1.7 and 3.0, respectively). The 2nd peak in the vertical ground reaction forces was similar across groups for all speed conditions (all $p > 0.05$). Mean values for the 2nd peak across groups were 1.10, 1.02 and 1.18 N/BW for the comfortable, slow and fast speed conditions, respectively.

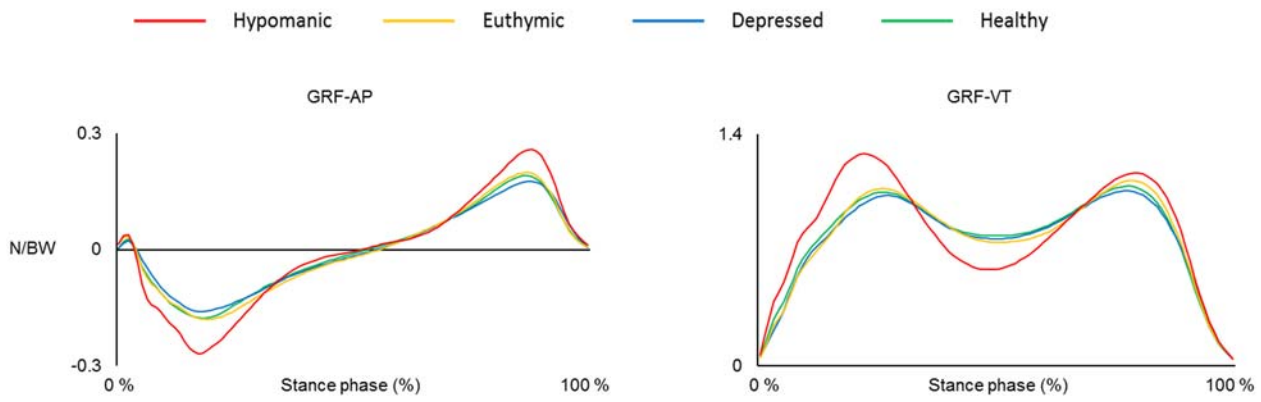

Fig. 4.15. Mean ground reaction forces (GRF) for each group in the anteroposterior (AP, left) and vertical (VT, right) directions during stance phase for the comfortable speed condition.

The relationships between gait speed and peaks in the anteroposterior and vertical ground reaction forces for each speed condition are shown in Fig. 4.16 and Fig. 4.17, respectively. Peaks in the anteroposterior direction depended on gait speed for all speed conditions (all $p < 0.05$), and peaks in the vertical direction depended on gait speed for all speed conditions except for the 1st

peak and valley for the slow speed condition, and for the 2nd peak for the fast speed condition (Table 4.14). When the effect of gait speed and groups on peaks in the anteroposterior and vertical ground reaction forces were separated using the linear mixed model, significant differences between groups were found for all speed conditions (Table 4.14). The positive peak in the anteroposterior ground reaction forces was greater for the hypomanic group than for the depressed group and healthy controls for the slow speed condition (all $p < 0.05$; $d = 1.0$ and 1.7, respectively) and the negative peak in the anteroposterior ground reaction forces was greater for the hypomanic group than for the depressed group and healthy controls for the comfortable speed condition (all $p < 0.05$). The 1st peak in the vertical ground reaction forces was greater for the hypomanic group than for the other groups for the comfortable speed condition (all $p < 0.05$), and was less for the depressed group than for the hypomanic group and the euthymic group for the slow speed condition (all $p < 0.05$; $d = 1.2$ and 1.3, respectively). The 2nd peak in the vertical ground reaction forces was greater for the euthymic group than for the depressed group for the fast speed condition ($p < 0.05$; $d = 0.9$). The valley in the vertical ground reaction forces was greater for healthy controls than for the hypomanic group and the depressed group for the comfortable speed condition (all $p < 0.05$; $d = 3.0$ and 0.2, respectively), than for the depressed group for the slow speed condition ($p < 0.05$; $d = 0.8$), and for the hypomanic group for the fast speed condition ($p < 0.05$; $d = 2.4$).

Table 4.11
Mean values for peak ground reaction forces (GRF) (N/BW) in the anteroposterior (AP) and vertical (VT) directions for each speed condition and group

	Hypomanic	Euthymic	Depressed	Healthy
N	4	6	10 (9 for slow)	14
Slow				
Peak positive GRF-AP	0.17 (0.04)^{HC*}	0.13 (0.03)	0.12 (0.05)	0.12 (0.03)^{HM*}
Peak negative GRF-AP	0.15 (0.04)	0.12 (0.02)	0.12 (0.05)	0.11 (0.02)
1st peak GRF-VT	1.06 (0.05)^{DP*}	1.04 (0.03)	1.00 (0.05)^{HM*}	1.03 (0.03)
2nd peak GRF-VT	1.05 (0.02)	1.03 (0.03)	1.00 (0.05)	1.02 (0.04)
GRF-VT valley	0.83 (0.09)	0.84 (0.05)	0.80 (0.06)	0.85 (0.06)
Comfortable				
Peak positive GRF-AP	0.26 (0.02)^{HC*,DP**}	0.21 (0.03)	0.18 (0.05)^{HM**}	0.19 (0.03)^{HM*}
Peak negative GRF-AP	0.27 (0.04)^{HC**,EU**,DP**}	0.18 (0.03)^{HM**}	0.17 (0.05)^{HM**}	0.18 (0.03)^{HM**}
1st peak GRF-VT	1.29 (0.13)^{HC***,EU**,DP**}	1.09 (0.07)^{HM**}	1.08 (0.10)^{HM**}	1.07 (0.06)^{HM***}
2nd peak GRF-VT	1.17 (0.08)	1.13 (0.07)	1.07 (0.08)	1.09 (0.07)
GRF-VT valley	0.56 (0.07)^{HC**,EU*,DP**}	0.73 (0.07)^{HM*}	0.75 (0.11)^{HM**}	0.77 (0.07)^{HM**}
Fast				
Peak positive GRF-AP	0.31 (0.03)	0.29 (0.03)	0.28 (0.05)	0.27 (0.05)
Peak negative GRF-AP	0.33 (0.04)	0.27 (0.05)	0.28 (0.07)	0.26 (0.05)
1st peak GRF-VT	1.49 (0.19)	1.26 (0.13)	1.34 (0.17)	1.30 (0.13)
2nd peak GRF-VT	1.23 (0.10)	1.26 (0.10)	1.13 (0.14)	1.16 (0.10)
GRF-VT valley	0.31 (0.08)	0.49 (0.12)	0.44 (0.12)	0.50 (0.14)

Note: Values in parentheses are standard deviations. Superscript letters are significant differences between groups based on multiple comparisons using one-way ANOVA with Tukey post-hoc analysis: HM=Hypomanic, EU=Euthymic, DP=Depressed, HC=Healthy. * $p < .05$. ** $p < .01$. *** $p < .001$.

Table 4.12

Estimates and 95% confidence intervals for peak ground reaction forces (GRF) (N/BW) in the anteroposterior (AP) and vertical (VT) directions based on the linear mixed model

	Gait speed	Healthy vs. Hypomanic	Euthymic vs. Hypomanic	Depressed vs. Hypomanic	Healthy vs. Euthymic	Depressed vs. Euthymic	Healthy vs. Depressed
Slow							
Peak pos GRF-AP	**0.15***** **(0.13, 0.17)**	**-0.02*** **(-0.04, 0.00)**	-0.01 (-0.03, 0.01)	**-0.02*** **(-0.04, 0.00)**	-0.01 (-0.02, 0.01)	-0.01 (-0.03, 0.01)	0.002 (-0.01, 0.02)
Peak neg GRF-AP	**-0.13***** **(-0.15, -0.10)**	0.01 (-0.01, -0.03)	0.01 (-0.02, 0.03)	0.01 (-0.02, 0.03)	0.01 (-0.01, 0.02)	0.001 (-0.02, 0.02)	0.01 (-0.01, 0.02)
1st peak GRF-VT	-0.02 (-0.08, 0.03)	-0.04 (-0.08, 0.01)	-0.02 (-0.07, 0.03)	**-0.07**** **(-0.11, -0.02)**	-0.01 (-0.05, 0.02)	**-0.04*** **(-0.08, 0.00)**	0.03 (0.00, 0.06)
2nd peak GRF-VT	**0.08**** **(0.04, 0.13)**	-0.005 (-0.05, 0.04)	0.01 (-0.04, 0.05)	-0.03 (-0.08, 0.01)	-0.01 (-0.05, 0.02)	-0.04 (-0.08, 0.00)	0.03 (0.00, 0.06)
Valley GRF-VT	0.07 (-0.03, 0.16)	0.04 (-0.03, 0.12)	0.02 (-0.06, 0.11)	-0.02 (-0.10, 0.06)	0.02 (-0.04, 0.08)	-0.04 (-0.01, 0.02)	**0.06*** **(0.01, 0.11)**
Comfortable							
Peak pos GRF-AP	**0.16***** **(0.14, 0.19)**	-0.01 (-0.04, 0.01)	-0.003 (-0.03,0.03)	-0.02 (-0.05, 0.01)	-0.01 (-0.03, 0.01)	-0.01 (-0.04, 0.01)	0.003 (-0.02, 0.02)
Peak neg GRF-AP	**-0.16***** **(-0.20, -0.12)**	**0.04*** **(-0.01, 0.07)**	0.03 (0.00, 0.07)	**0.04*** **(0.01, 0.07)**	0.003 (-0.02, 0.03)	0.01 (-0.02, 0.03)	-0.003 (-0.02, 0.02)
1st peak GRF-VT	**0.32***** **(0.24, 0.40)**	**-0.11*** **(-0.18, -0.04)**	**-0.09*** **(-0.17, -0.01)**	**-0.08*** **(-0.16, -0.01)**	-0.02 (-0.07, 0.04)	0.01 (-0.05, 0.07)	-0.03 (-0.08, 0.02)
2nd peak GRF-VT	**0.18***** **(0.10, 0.25)**	-0.02 (-0.09, 0.05)	0.02 (-0.06, 0.10)	-0.03 (-0.10, 0.05)	-0.03 (-0.09, 0.02)	-0.04 (-0.10, 0.02)	0.01 (-0.04, 0.06)
Valley GRF-VT	**-0.38***** **(-0.44, -0.31)**	**0.09**** **(0.03, 0.15)**	0.05 (-0.02, 0.12)	0.04 (-0.02, 0.10)	0.04 (-0.08, 0.09)	-0.01 (-0.06, 0.04)	**0.05*** **(0.01, 0.09)**
Fast							
Peak pos GRF-AP	**0.06**** **(0.03, 0.10)**	-0.04 (-0.08, 0.01)	0.001 (-0.05, 0.05)	-0.02 (-0.07, 0.03)	-0.04 (-0.08, 0.00)	-0.02 (-0.06, 0.02)	-0.02 (-0.05, 0.02)
Peak neg GRF-AP	**-0.06**** **(-0.11, -0.02)**	0.06 (0.00, 0.11)	0.04 (-0.02, 0.11)	0.04 (-0.02, 0.10)	0.01 (-0.03, 0.06)	-0.00002 (-0.05, 0.05)	0.01 (-0.03, 0.05)
1st peak GRF-VT	**0.34***** **(0.23, 0.44)**	-0.13 (-0.27, 0.01)	-0.12 (-0.28, 0.04)	-0.07 (-0.22, 0.08)	-0.01 (-0.13, 0.11)	0.05 (-0.08, 0.18)	-0.06 (-0.16, 0.05)
2nd peak GRF-VT	-0.03 (-0.13, 0.07)	-0.10 (-0.24, 0.03)	-0.01 (-0.16, 0.15)	0.13 (-0.27, 0.00)	-0.10 (-0.21, 0.02)	**-0.13*** **(-0.25, -0.01)**	0.03 (-0.07, 0.13)
Valley GRF-VT	**-0.29***** **(-0.36, -0.21)**	**0.13*** **(0.02, 0.24)**	0.08 (-0.05, 0.21)	0.06 (-0.06, 0.17)	0.05 (-0.05, 0.14)	-0.03 (-0.13, 0.07)	0.07 (-0.01, 0.15)

Note: Values in parentheses are lower and upper bounds for 95% confidence intervals. Bold fonts with asterisks indicate significant differences between groups. * $p < .05$. ** $p < .01$. *** $p < .001$.

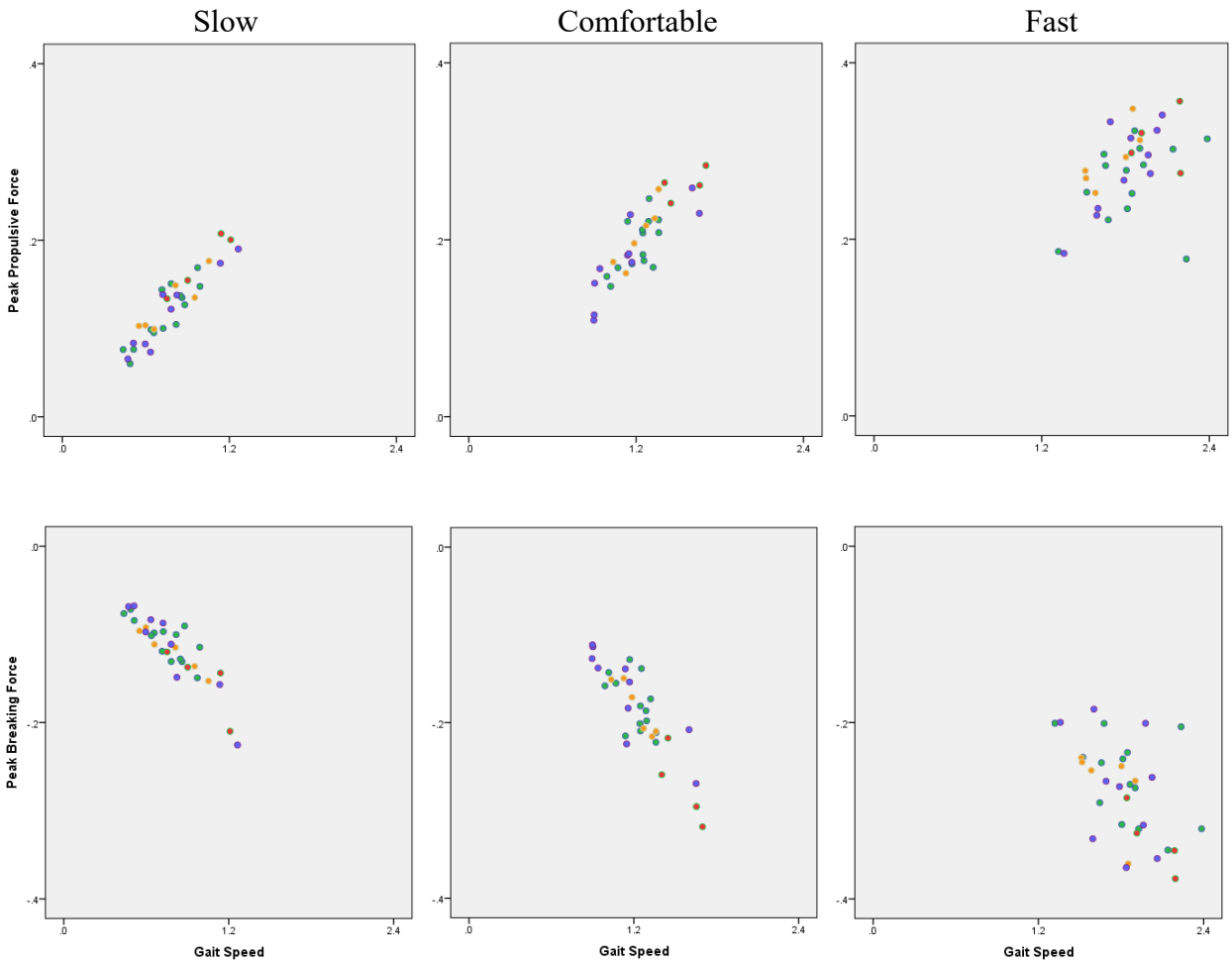

Fig. 4.16. The relationships between gait speed and the positive (top row) and negative (bottom row) peaks in the anteroposterior ground reaction forces for the slow (left column), comfortable (middle column) and fast speed (right column) conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group, blue for the depressed group and green for healthy controls. All were significantly related to gait speed.

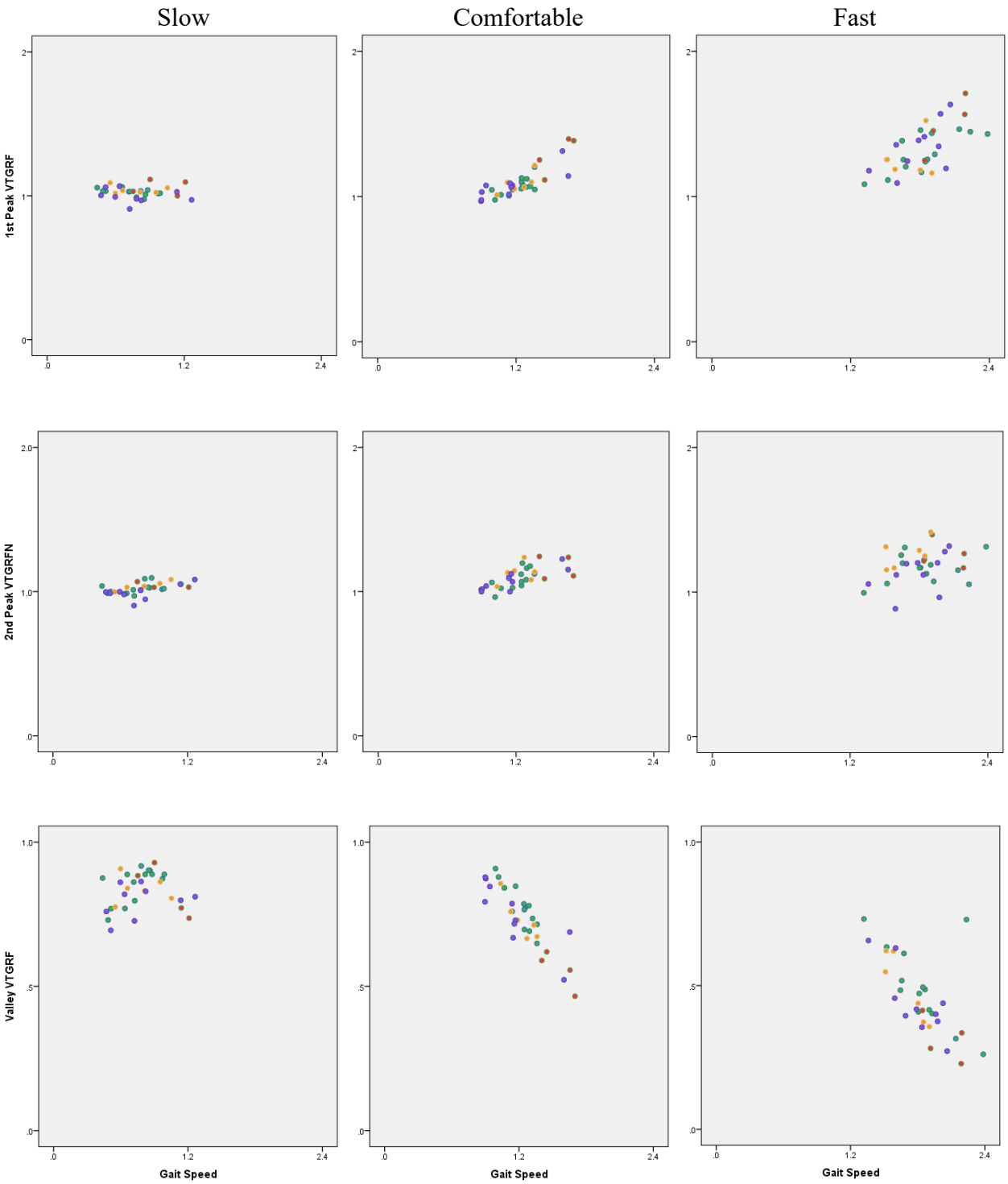

Fig. 4.17. The relationships between gait speed, the 1st peak 1st (top row) and the 2nd peak (middle row) and the valley (bottom row) in ground reaction forces (GRF) in the vertical (VT) direction for the slow (left column), comfortable (middle column) and fast speed (right column) conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group, blue for the depressed group and green for healthy controls.

4.4.4.2 Peak joint torques

Mean flexor and extensor torques for the hip and knee, and mean dorsiflexor and plantarflexor torques for the ankle for each group during stance phase are shown for the comfortable speed condition in Fig. 4.18. Across all speed conditions, peak flexor and extensor torques at the hip and knee, and peak dorsiflexor and plantarflexor torques at the ankle tended to be greater for the hypomanic group than for the other groups (Table 4.15). Peak hip extensor torques were 81.3, 90.0 and 56.5% greater for the hypomanic group than for the euthymic group, the depressed group and healthy controls, respectively, for the comfortable speed condition (all $p < 0.05$; $d = 5.3$, 2.2 and 2.5, respectively). Peak knee flexor torques were 54.8, 71.1 and 44.4% greater for the hypomanic group than for the euthymic group, the depressed group and healthy controls, respectively, for the comfortable speed condition (all $p < 0.05$; $d = 3.3$, 2.1 and 2.5, respectively). Peak ankle plantarflexor torque was 23.1% greater for the hypomanic group than for the depressed group ($p < 0.05$; $d = 1.4$). No significant differences between groups were found for any joint torques for the slow and fast speed conditions.

The relationship between gait speed and peak joint torques for each speed condition are shown in Fig. 4.19 and Fig. 4.20. Peak flexor and extensor torques in the hip and knee, and peak dorsiflexor and plantarflexor torques in the ankle depended on gait speed for all speed conditions (all $p < 0.05$) except for peak ankle plantarflexor torques for fast speed condition (Table 4.16). After accounting for the effect of gait speed, peak hip extensor torque was greater for the hypomanic group than for the euthymic group and the depressed group for the comfortable speed condition (all $p < 0.05$). Peak hip flexor torque was greater for the euthymic group than for healthy controls for the comfortable speed condition ($p < 0.05$; $d = 1.0$), and greater for the euthymic group

than for the depressed group for the fast speed condition ($p < 0.05$; $d = 0.5$). Peak knee flexor torque was greater for the hypomanic group than for the depressed group for the comfortable speed condition ($p < 0.05$).

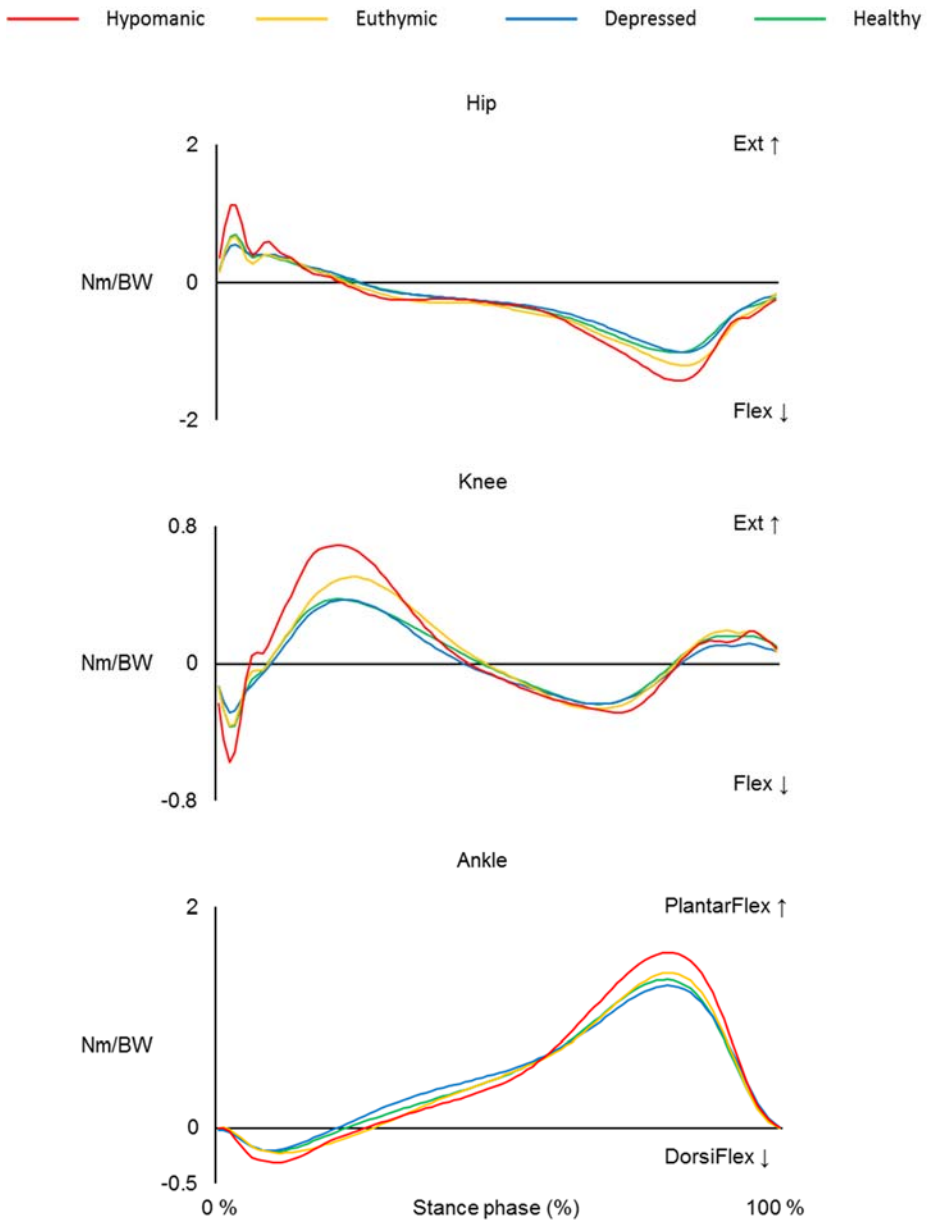

Fig. 4.18. Mean extensor-flexor torques for each group for the hip (top), knee (middle) and ankle (bottom) during stance phase for the comfortable speed condition.

Table 4.13
Mean values for peak flexion and extension torques (Nm/BW) in the hip, knee and ankle for each speed condition and group

	Hypomanic	Euthymic	Depressed	Healthy
Slow				
Hip extension	0.72 (0.13)	0.41 (0.23)	0.42 (0.22)	0.43 (0.22)
Hip flexion	0.95 (0.18)	0.82 (0.29)	0.75 (0.38)	0.69 (0.18)
Knee extension	0.31 (0.22)	0.25 (0.17)	0.21 (0.15)	0.22 (0.11)
Knee flexion	0.43 (0.15)	0.33 (0.11)	0.28 (0.10)	0.31 (0.11)
Ankle plantarflexion	1.37 (0.17)	1.19 (0.16)	1.10 (0.22)	1.12 (0.20)
Ankle dorsiflexion	0.17 (0.05)	0.14 (0.05)	0.15 (0.08)	0.14 (0.05)
Comfortable				
Hip extension	1.33 (0.24)^{HC**,EU**,DP***}	0.75 (0.11)^{HM**}	0.70 (0.29)^{HM***}	0.85 (0.19)^{HM**}
Hip flexion	1.44 (0.23)	1.23 (0.22)	1.03 (0.49)	1.03 (0.21)
Knee extension	0.71 (0.32)	0.52 (0.18)	0.40 (0.22)	0.43 (0.16)
Knee flexion	0.65 (0.18)^{HC*,EU*,DP***}	0.42 (0.07)^{HM*}	0.38 (0.13)^{HM***}	0.45 (0.08)^{HM*}
Ankle plantarflexion	1.60 (0.17)^{DP*}	1.42 (0.12)	1.30 (0.21)^{HM*}	1.35 (0.13)
Ankle dorsiflexion	0.33 (0.07)	0.24 (0.07)	0.21 (0.09)	0.23 (0.07)
Fast				
Hip extension	2.11 (0.39)	1.34 (0.27)	1.54 (0.52)	1.54 (0.46)
Hip flexion	1.79 (0.27)	1.76 (0.29)	1.49 (0.52)	1.57 (0.34)
Knee extension	1.02 (0.38)	0.99 (0.38)	0.94 (0.40)	0.83 (0.25)
Knee flexion	0.76 (0.19)	0.62 (0.11)	0.64 (0.18)	0.64 (0.25)
Ankle plantarflexion	1.76 (0.31)	1.67 (0.19)	1.51 (0.21)	1.52 (0.18)
Ankle dorsiflexion	0.46 (0.09)	0.37 (0.12)	0.38 (0.08)	0.38 (0.13)

Note: Values in parentheses are standard deviations. Superscript letters are significant differences between groups based on multiple comparisons using one-way ANOVA with Tukey post-hoc analysis: HM=Hypomanic, EU=Euthymic, DP=Depressed, HC=Healthy. * $p < .05$. ** $p < .01$. *** $p < .001$.

Table 4.14
Estimates and 95% confidence intervals for peak joint torques based on the linear mixed model

	Gait speed	Healthy vs. Hypomanic	Euthymic vs. Hypomanic	Depressed vs. Hypomanic	Healthy vs. Euthymic	Depressed vs. Euthymic	Healthy vs. Depressed
Slow							
Hip ext	**0.73***** **(0.54, 0.93)**	-0.09 (-0.29, 0.11)	-0.14 (-0.36, 0.08)	0.13 (-0.34, 0.08)	0.05 (-0.12, 0.22)	0.01 (-0.17, 0.19)	0.04 (-0.10, 0.19)
Hip flex	**-0.63***** **(-0.75, -0.50)**	0.09 (-0.11, 0.29)	-0.01 (-0.24, 0.21)	0.06 (-0.15, 0.27)	0.11 (-0.06, 0.27)	0.07 (-0.11, 0.24)	0.03 (-0.11, 0.18)
Knee ext	**0.40***** **(0.25, 0.54)**	0.02 (-0.16, 0.20)	0.03 (-0.17, 0.23)	-0.003 (-0.19, 0.19)	-0.01 (-0.16, 0.14)	-0.03 (-0.20, 0.13)	0.02 (-0.11, 0.15)
Knee flex	**-0.27***** **(-0.39, -0.15)**	0.05 (-0.08, 0.18)	0.04 (-0.11, 0.18)	0.09 (-0.05, 0.23)	0.01 (-0.10, 0.12)	0.06 (-0.06, 0.17)	-0.04 (-0.14, 0.05)
Ankle pf	**0.58***** **(0.42, 0.74)**	-0.10 (-0.27, 0.08)	-0.04 (-0.24, 0.16)	-0.13 (-0.32, 0.06)	-0.06 (-0.21, 0.09)	-0.09 (-0.25, 0.07)	0.04 (-0.09, 0.17)
Ankle df	**-0.18***** **(-0.24, -0.11)**	-0.02 (-0.08, 0.04)	-0.01 (-0.08, 0.06)	-0.01 (-0.07, 0.05)	-0.01 (-0.06, 0.04)	-0.001 (-0.05, 0.05)	-0.005 (-0.05, 0.04)
Comfortable							
Hip ext	**0.84***** **(0.59, 1.08)**	-0.20 (-0.42, 0.01)	**-0.30*** **(-0.54, -0.06)**	**-0.29*** **(-0.52, -0.06)**	0.10 (-0.07, 0.27)	0.01 (-0.17, 0.19)	0.226 (-0.06, 0.24)
Hip flex	**-0.93***** **(-1.08, -0.79)**	0.10 (-0.14, 0.34)	-0.10 (-0.37, 0.17)	0.03 (-0.21, 0.28)	**0.20*** **(0.00, 0.04)**	0.13 (-0.08, 0.35)	0.06 (-0.10, 0.23)
Knee ext	**0.53***** **(0.32, 0.75)**	-0.10 (-0.34, 0.14)	-0.01 (-0.29, 0.26)	-0.09 (-0.35, 0.16)	-0.09 (-0.29, 0.11)	-0.08 (-0.29, 0.13)	-0.01 (-0.18, 0.16)
Knee flex	**-0.32***** **(-0.46, -0.18)**	0.09 (-0.03, 0.22)	0.12 (-0.01, 0.26)	**0.14*** **(0.01, 0.27)**	-0.03 (-0.13, 0.07)	0.02 (-0.09, 0.12)	-0.05 (-0.13, 0.03)
Ankle pf	**0.47***** **(0.32, 0.62)**	-0.09 (-0.26, 0.08)	-0.03 (-0.22, 0.17)	-0.10 (-0.28, 0.08)	-0.06 (-0.20, 0.08)	-0.08 (-0.23, 0.07)	0.01 (-0.11, 0.13)
Ankle df	**-0.24***** **(-0.31, -0.17)**	0.02 (-0.05, 0.09)	0.01 (-0.07, 0.09)	0.02 (-0.06, 0.10)	0.01 (-0.05, 0.07)	0.01 (-0.05, 0.07)	0.001 (-0.05, 0.05)
Fast							
Hip ext	**1.55***** **(1.23, 1.86)**	-0.27 (-0.66, 0.13)	-0.24 (-0.70, 0.21)	-0.19 (-0.61, 0.22)	-0.02 (-0.36, 0.31)	0.05 (-0.31, 0.40)	-0.07 (-0.35, 0.21)
Hip flex	**-0.61***** **(-0.78, -0.43)**	0.10 (-0.25, 0.46)	-0.17 (-0.58, 0.24)	0.16 (-0.22, 0.53)	0.27 (-0.03, 0.58)	**0.33*** **(0.00, 0.65)**	-0.05 (-0.31, 0.21)
Knee ext	**0.40***** **(0.20, 0.60)**	-0.10 (-0.47, 0.27)	0.11 (-0.32, 0.53)	0.02 (-0.36, 0.41)	-0.21 (-0.53, 0.11)	-0.08 (-0.42, 0.25)	-0.13 (-0.40, 0.14)
Knee flex	**-0.47***** **(-0.62, -0.31)**	0.04 (-0.16, 0.24)	-0.02 (-0.25, 0.21)	0.01 (-0.20, 0.22)	0.05 (-0.12, 0.22)	0.03 (-0.15, 0.21)	0.02 (-0.12, 0.17)
Ankle pf	0.02 (-0.14, 0.17)	-0.24 (-0.48, 0.00)	-0.09 (-0.37, 0.19)	-0.25 (-0.50, 0.01)	-0.15 (-0.36, 0.06)	-0.16 (-0.38, 0.06)	0.01 (-0.17, 0.18)
Ankle df	**-0.22***** **(-0.28, -0.15)**	0.04 (-0.07, 0.15)	0.02 (-0.11, 0.14)	0.03 (-0.09, 0.14)	0.03 (-0.07, 0.12)	0.01 (-0.09, 0.11)	0.01 (-0.06, 0.09)

Note: Values in parentheses are lower and upper bounds for 95% confidence intervals. Bold fonts with asterisks indicate significant differences between groups. * $p < .05$. ** $p < .01$. *** $p < .001$.

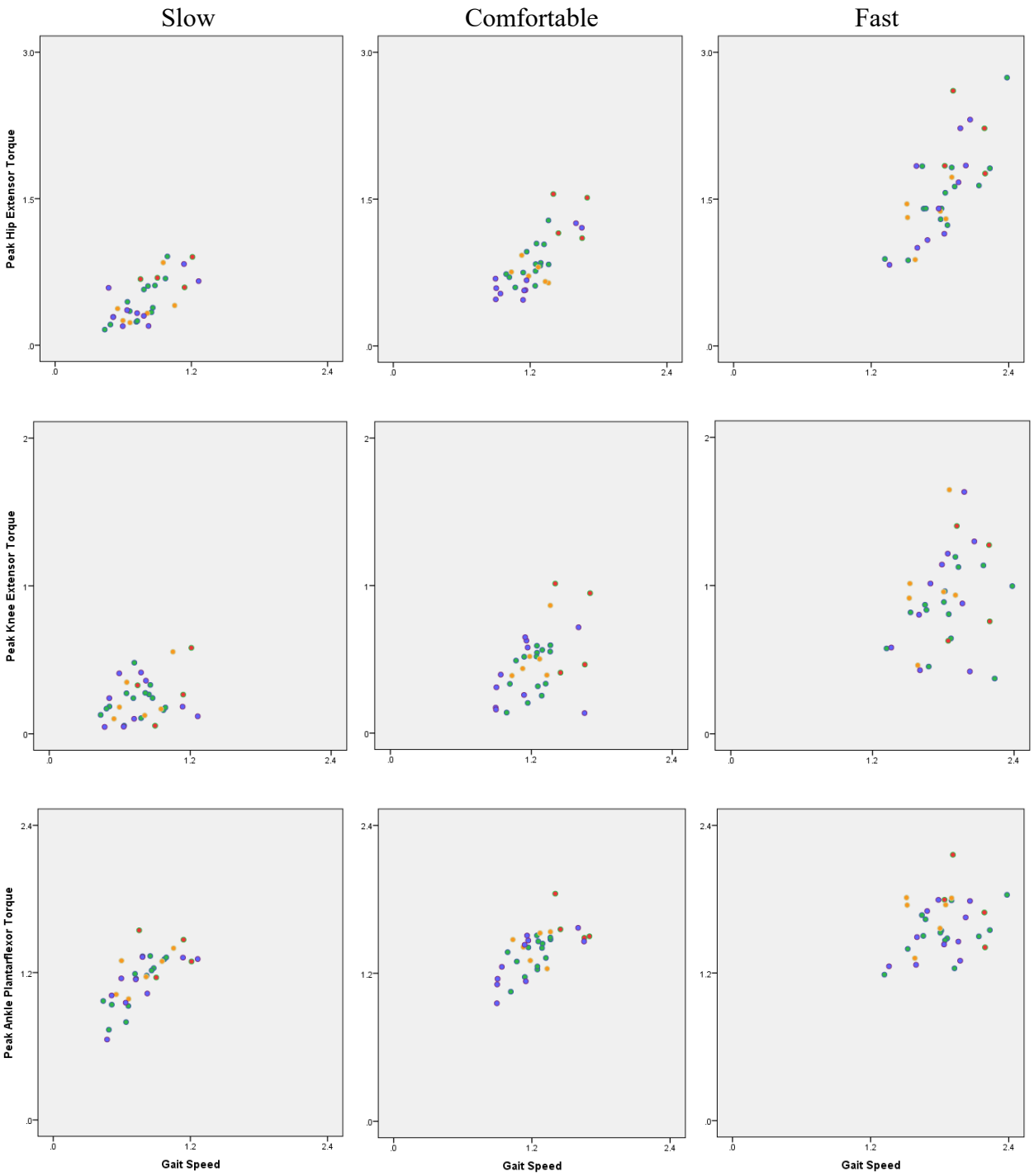

Fig. 4.19. The relationships between gait speed and peak extensor and plantarflexor torques in the hip (top row), knee (middle row), and ankle (bottom row) for the slow (left column), comfortable (middle column) and fast speed (right column) conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group, blue for the depressed group and green for healthy controls.

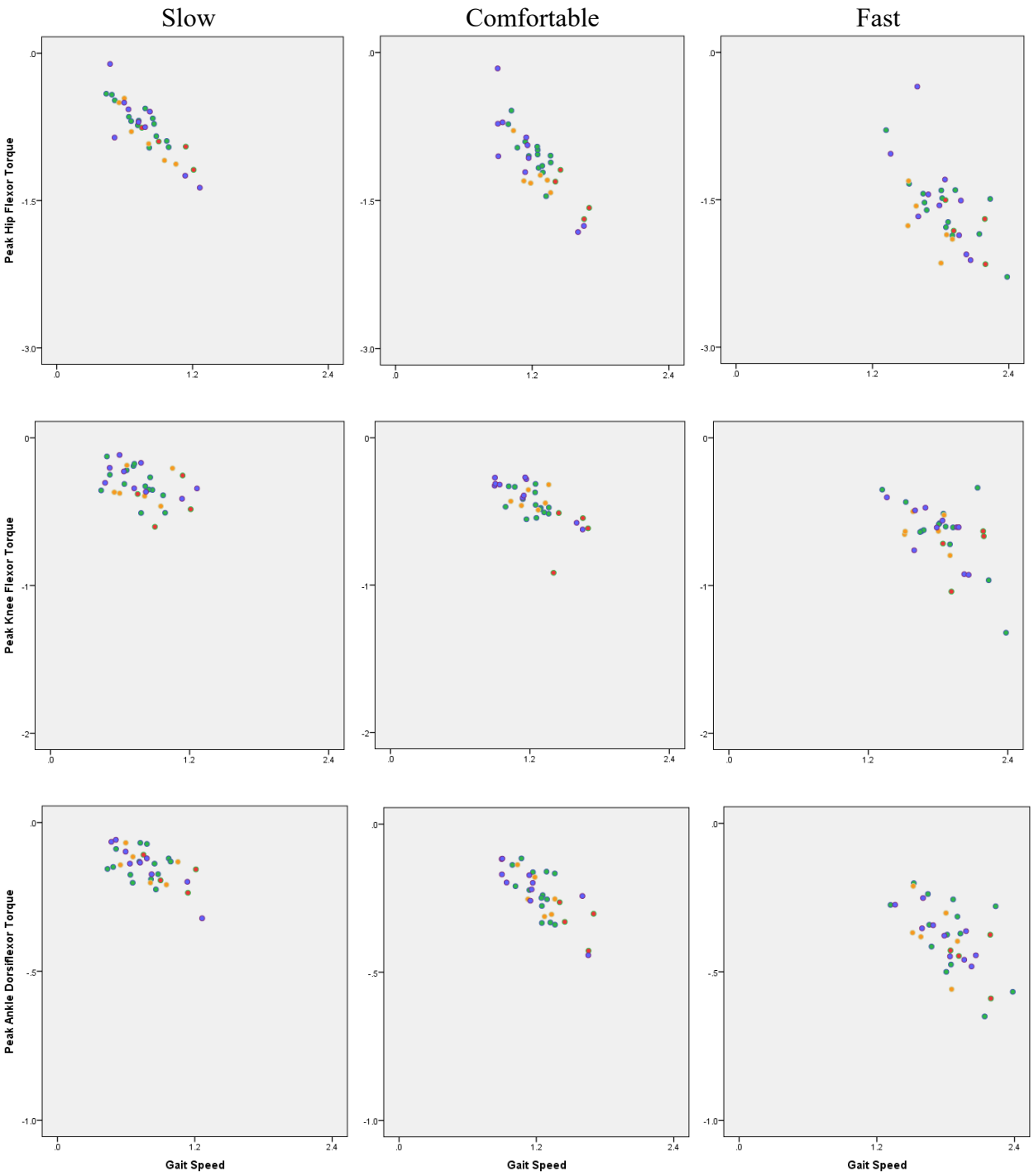

Fig. 4.20. The relationships between gait speed and peak flexor and dorsiflexor torques in the hip (top row), knee (middle row), and ankle (bottom row) for the slow (left column), comfortable (middle column) and fast speed (right column) conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group, blue for the depressed group and green for healthy controls. All were significantly related to gait speed.

4.4.4.3 Peak joint power generation

Mean joint power at the hip, knee and ankle for each group during stance phase are shown for the comfortable speed condition in Fig. 4.21. Peak power generation at the ankle was significantly different between groups for all speed conditions (Table 4.17). Peak power generation at the ankle was 72.3, 71.2 and 54.2% greater for the hypomanic group than for the euthymic group, the depressed group and healthy controls, respectively, for the comfortable speed condition (all $p < 0.05$; $d = 4.1$, 1.7 and 3.0, respectively), and 120.7 and 94.3% greater for the hypomanic group than for the euthymic group and healthy controls, respectively, for the slow speed condition (all $p < 0.05$), and 42.9% greater for the hypomanic group than for the euthymic group for the fast speed condition ($p < 0.05$). Peak power generation at the knee for the comfortable and slow speed conditions were significantly different between groups (Table 4.17). Peak power generation at the knee was 127.5, 176.0 and 117.9% greater for the hypomanic group than for the euthymic group, the depressed group and healthy controls, respectively, for the comfortable speed condition (all $p < 0.05$; $d = 5.0$, 2.4 and 3.4, respectively), and was 157.7% greater for the hypomanic group than for healthy controls for the slow speed condition ($p < 0.05$; $d = 2.9$). Peak power generation at the hip was not significantly different between groups (Table 4.17).

The relationships between gait speed and peak power generation at the hip, knee and ankle for each speed condition are shown in Fig. 4.22. For all speed conditions, peak power generation at the hip, knee and ankle increased with gait speed (all $p < 0.05$) (Table 4.18). When the effect of gait speed and groups were separated, peak hip power generation was greater for the euthymic group than for healthy controls for the comfortable speed condition ($p < 0.05$; $d = 0.9$). Peak ankle power generation was greater for the hypomanic group than for the euthymic group, the depressed

group and healthy controls for the slow (all $p < 0.05$; $d = 2.5$, 1.6 and 2.1, respectively) and fast speed conditions (all $p < 0.05$; $d = 2.3$, 1.3 and 1.7, respectively), and for the euthymic group for the comfortable speed condition ($p < 0.05$).

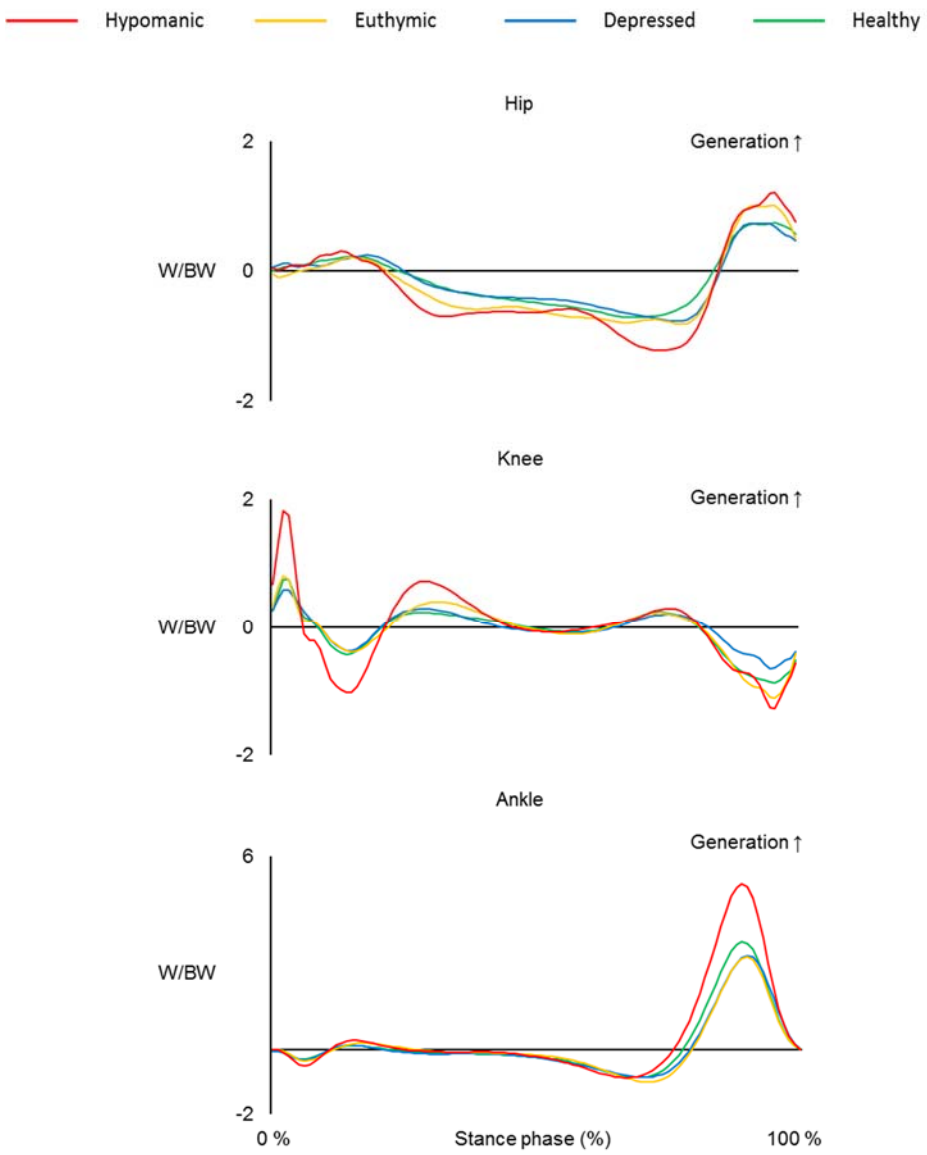

Fig. 4.21. Mean joint powers for each group at the hip (top), knee (middle) and ankle (bottom) during stance phase for the comfortable speed condition.

Table 4.15
Mean values for peak joint power generation (W/BW) at the hip, knee and ankle for each speed condition and group

	Hypomanic	Euthymic	Depressed	Healthy
Slow				
Hip	0.80 (0.31)	0.62 (0.32)	0.51 (0.28)	0.45 (0.24)
Knee	0.67 (0.59)^{HC*}	0.29 (0.09)	0.30 (0.19)	0.26 (0.14)^{HM*}
Ankle	3.09 (1.43)^{HC*,EU*}	1.40 (0.68)^{HM*}	1.67 (0.91)	1.59 (0.72)^{HM*}
Comfortable				
Hip	1.34 (0.27)	1.18 (0.38)	0.96 (0.51)	0.88 (0.33)
Knee	2.07 (1.01)^{HC**,EU**,DP**}	0.91 (0.23)^{HM**}	0.75 (0.54)^{HM**}	0.95 (0.33)^{HM**}
Ankle	5.29 (0.72)^{HC**,EU**,DP**}	3.07 (0.54)^{HM**}	3.09 (1.27)^{HM**}	3.43 (0.62)^{HM**}
Fast				
Hip	2.04 (0.24)	2.06 (0.60)	1.98 (0.68)	1.99 (1.11)
Knee	2.69 (1.20)	2.09 (0.75)	2.36 (1.13)	2.11 (1.15)
Ankle	7.13 (1.49)^{EU*}	4.99 (0.93)^{HM*}	5.30 (1.38)	5.46 (1.01)

Note: Values in parentheses are standard deviations. Superscript letters are significant differences between groups based on multiple comparisons using one-way ANOVA with Tukey post-hoc analysis: HM=Hypomanic, EU=Euthymic, DP=Depressed, HC=Healthy. * $p < .05$. ** $p < .01$.

Table 4.16
Estimates and 95% confidence intervals for peak joint power generation based on the linear mixed model

	Gait speed	Healthy vs. Hypomanic	Euthymic vs. Hypomanic	Depressed vs. Hypomanic	Healthy vs. Euthymic	Depressed vs. Euthymic	Healthy vs. Depressed
Slow							
Hip	**0.90***** **(0.72, 1.09)**	-0.11 (-0.30, 0.09)	0.03 (-0.19, 0.25)	-0.08 (-0.29, 0.12)	-0.14 (-0.03, 0.03)	-0.11 (-0.29, 0.06)	-0.03 (-0.17, 0.12)
Knee	**0.85***** **(0.59, 1.11)**	-0.18 (-0.43, 0.07)	-0.18 (-0.46, 0.10)	-0.18 (-0.44, 0.09)	-0.003 (-0.21, 0.20)	0.002 (-0.22, 0.23)	-0.005 (-0.19, 0.18)
Ankle	**3.71***** **(3.25, 4.16)**	**-0.52*** **(-1.01, -0.02)**	**-0.83**** **(-1.39, -0.27)**	**-0.57*** **(-1.09, -0.04)**	0.31 (-0.10, 0.73)	0.26 (-0.19, 0.71)	0.05 (-0.32, 0.41)
Comfortable							
Hip	**1.17***** **(0.86, 1.47)**	-0.06 (-0.40, 0.28)	0.23 (-0.15, 0.61)	0.09 (-0.27, 0.45)	**-0.29*** **(-0.57, -0.02)**	-0.14 (-0.44, 0.15)	-0.15 (-0.39, 0.09)
Knee	**1.95***** **(1.34, 2.56)**	-0.46 (-1.00, 0.08)	-0.51 (-1.12, 0.09)	-0.53 (-1.11, 0.04)	0.05 (-0.38, 0.48)	-0.02 (-0.48, 0.43)	0.07 (-0.29, 0.44)
Ankle	**3.63***** **(2.84, 4.42)**	-0.64 (-1.44, 0.16)	**-1.01*** **(-1.91, -0.11)**	-0.75 (-1.60, 0.10)	0.37 (-0.28, 1.02)	0.27 (-0.43, 0.96)	0.11 (-0.45, 0.66)
Fast							
Hip	**1.95***** **(1.44, 2.46)**	0.33 (-0.47, 1.13)	0.68 (-0.24, 1.60)	0.41 (-0.42, 1.25)	-0.35 (-1.04, 0.33)	-0.27 (-0.99, 0.46)	-0.09 (-0.67, 0.50)
Knee	**2.58***** **(1.77, 3.40)**	-0.08 (-1.21, 1.04)	0.28 (-1.02, 1.57)	0.30 (-0.88, 1.48)	-0.36 (-1.32, 0.61)	0.02 (-0.99, 1.04)	-0.38 (-1.20, 0.44)
Ankle	**1.64**** **(0.69, 2.59)**	**-1.34*** **(-2.65, -0.04)**	**-1.58*** **(-3.09, -0.08)**	**-1.43*** **(-2.79, -0.06)**	0.24 (-0.88, 1.36)	0.16 (-1.02, 1.34)	0.08 (-0.86, 1.03)

Note: Values in parentheses are lower and upper bounds for 95% confidence intervals. Bold fonts with asterisks indicate significant differences between groups. * $p < .05$. ** $p < .01$. *** $p < .001$.

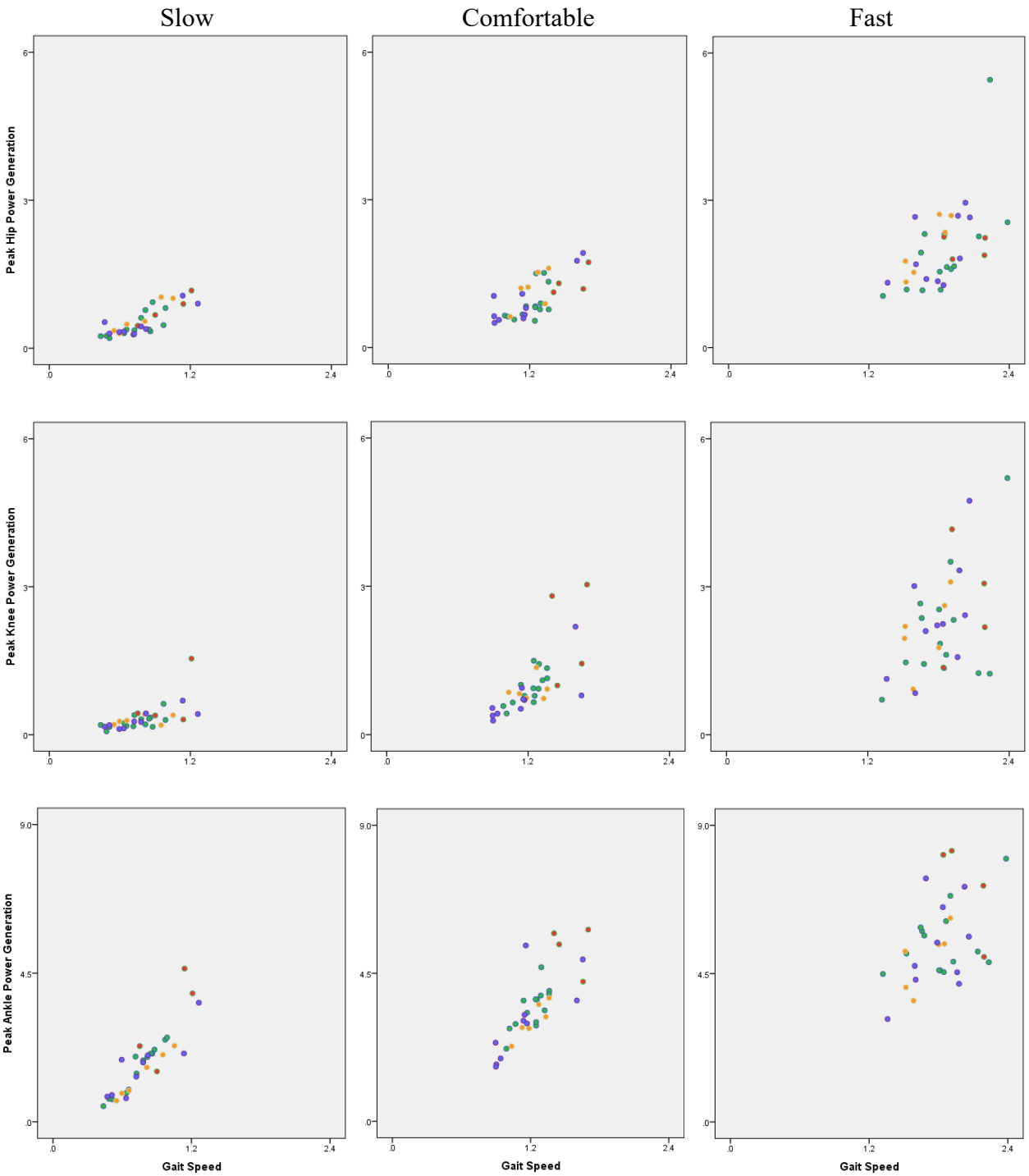

Fig. 4.22. The relationships between gait speed and peak power generation in the hip (top row), knee (middle row), and ankle (bottom row) for the slow (left column), comfortable (middle column) and fast speed (right column) conditions. Each dot represents one participant. Colors represent the following: red for the hypomanic group, yellow for the euthymic group, blue for the depressed group and green for healthy controls. All were significantly related to gait speed.

4.5 Discussion

In this study, the effect of mood phase on a day-to-day task, gait, was quantified using biomechanical analysis for the first time for individuals with bipolar disorder. The key finding was that the hypomanic group was associated with faster gait speed compared to the other groups for the comfortable speed condition. In addition, the hypomanic group was associated with greater ground reaction forces and greater power generation in the lower extremity compared to other groups, which was due not only to the effects of faster gait speed but also to mood phase itself. Although the depressed group tended to walk slower for the comfortable speed condition compared to the other groups, the difference was not significant because of two "fast" depressed individuals. When the data from these two "fast" depressed individuals were excluded, the mean gait speed of the "slow" depressed subgroup was less than the other groups, as might be expected. Another key finding was that gait speed for the euthymic group whose mood phase was normal and stable was the same as healthy controls for the comfortable speed condition. For all bipolar disorder groups, most of the mood-related differences in gait characteristics were observed for the comfortable speed condition, and many of the significant differences did not persist when speed changed for the slow and fast speed conditions, suggesting that walking at comfortable speed best reflects mood phase for individuals with bipolar disorder.

Most importantly, as hypothesized, self-selected comfortable gait speed was faster for individuals in the hypomanic group. This result is consistent with the increased activity level, increased goal-directed activity and psychomotor agitation that DSM-5 emphasizes as a core symptom for mania/hypomania (American Psychiatric Association, 2013). Although assessment of activity level as measured in a time period of days is used for determining the clinical core

symptom for mania/hypomania (Cassidy et al., 1998; Minassian et al., 2010), the results from this study suggest that movement speed measured in a shorter time period (i.e., within a few seconds or minutes) may be as clinically relevant as activity level that is measured over a relatively longer period (i.e., for a few days or weeks), particularly for characterizing mania/hypomania. Since gait speed can be objectively measured in a short time period, measuring gait speed in individuals with bipolar disorder during a clinic visit may provide useful information about mood phase, particularly for mania/hypomania.

It was also hypothesized that the depressed group would be associated with slower gait speed. However, gait speed for individuals in the depressed group in this study was significantly slower only compared to individuals in the hypomanic group for the comfortable speed condition, and only tended to be slower compared to the euthymic group or healthy controls for the comfortable speed condition. Previous work has reported conflicting results for gait speed for depressed individuals (Lemke et al., 2000; Hausdorff et al., 2004; Michalak et al., 2009). Lemke et al. (2000) (inpatients with major depressive disorder off antidepressants) and Michalak et al. (2009) (inpatients with major depressive disorder on antidepressants) reported slower gait speed for depressed individuals than for healthy individuals. In contrast, Hausdorff et al. (2004) reported that gait speed tended to be slower, but not significantly, for individuals with bipolar disorder (with no mood phase reported) and major depressive disorder (on medication) compared to healthy individuals, which is consistent with the current findings for individuals in the depressed group.

In this study, the two "fast" individuals in the group of 10 individuals in the depressed group accounted for the similar gait speed for the depressed group compared to the euthymic group and healthy controls. When the two "fast" depressed individuals whose comfortable gait speed was over 4 standard deviations from the other eight "slow" depressed individuals were excluded

from the depressed group, mean gait speed for the "slow" depressed subgroup for the comfortable speed condition was significantly slower compared to the other groups, which is consistent with reports for major depressive disorder (Michalak et al. 2009). Although antidepressants have been reported to increase gait speed (Draganich et al. 2001; Paleacu et al. 2007), they do not account for the increased gait speed for the two "fast" depressed individuals in this study because one was not on an antidepressant and the other was not on any medications. Rather, five out of the other eight "slow" depressed individuals were on antidepressants like bupropion, citalopram, nortriptyline, trazodone, venlafaxine and vortioxetine. Furthermore, it is not likely that other comorbid psychiatric disorders accounted for the "fast" gait speed for the two depressed individuals or the "slow" gait speed for the other eight depressed individuals. The two "fast" depressed individuals did not have other comorbidities such as ADHD, anxiety disorder or post-traumatic stress disorder. Three of the other eight "slow" depressed individuals did not have other comorbidities, yet the mean gait speed of the two "fast" depressed individuals was 52% greater than for these other three "slow" depressed individuals. Additionally, comfortable gait speeds were similar for the three "slow" depressed individuals without comorbidities (1.07 m/s, SD = 0.15 m/s) and the other five "slow" depressed individuals with comorbidities (1.01 m/s, SD = 0.13 m/s). The difference in gait speed (0.56 m/s) between the two "fast" depressed individuals and three "slow" depressed individuals that have no comorbidities was more than the difference (0.06 m/s) in gait speed between the three "slow" depressed individuals with no comorbidities and the other five "slow" depressed individuals with comorbidities. Thus, the presence or absence of comorbid psychiatric disorders does not seem to explain differences in gait speeds among depressed individuals in this study.

An alternative explanation is that self-reports may not reflect actual motor disturbances in individuals with bipolar disorder. One item on the PHQ-9 asks participants to indicate how often they have experienced psychomotor symptoms ("*Moving or speaking so slowly that other people could have noticed? Or the opposite – being so fidgety or restless that you have been moving around a lot more than usual*") on a scale from 0 to 3 (0 = "not at all over the past two weeks"; 1 = "several days over the past two weeks"; 2 = "more than half the days over the past two weeks"; 3 = "nearly every day over the past two weeks"). On this psychomotor item, the two "fast" depressed individuals scored 3 and 1, but among the other eight "slow" depressed individuals, six scored 0 and two scored 1. Although it is not possible from the scores to determine whether individuals thought that their movements were slow or restless, the scores do suggest that the two "fast" individuals observed psychomotor symptoms on some or many days in the previous two weeks, but most of the "slow" depressed individuals did not. The results suggest that a self-report or maybe even a clinical interview does not necessarily capture "biological reality" as evidenced in this study. The discrepancy between self-report and "biological reality" is in line with previous studies that have reported the discrepancies between self-reported cognitive impairments and objectively measured cognitive performance (Burdick et al., 2005; Martínez-Arán et al., 2005; Svendsen et al., 2012). Results for the discrepancy between self-reported and objectively measured motor disturbances suggest that it may be necessary to objectively measure motor behavior for more accurately evaluating mood phase in individuals with bipolar disorder.

As expected, stride length, cadence and double limb support were significantly affected by gait speed for all speed conditions (Andriacchi et al., 1977; Kirtley et al., 1985), so that most of the significant differences between groups were explained by differences in gait speed. However, after accounting for gait speed, stride length was significantly longer and cadence was significantly

lower for individuals in the euthymic group for all speed conditions. For example, mean gait speed was the same for the euthymic group and healthy controls (1.21 m/s, SD 0.12 m/s) for the comfortable speed condition, but individuals in the euthymic group took longer and slower strides to achieve the same gait speed. Although mood is relatively normal during euthymia, these results suggest that the gait pattern in individuals in the euthymic group is different compared with healthy controls. The longer stride length used by individuals in the euthymic group to achieve the same gait speed with healthy controls may be associated with energetic inefficiencies for gait. Gordon et al. (2009) reported that metabolic energy cost increases when healthy individuals maintaining the same gait speed increase stride length from comfortable length to a longer length. That is, these results suggest that individuals in the euthymic group walking at the same speed as healthy controls may use more energy compared to healthy controls.

The effect of mood phase on upper body posture in individuals with bipolar disorder was related to gait speed for the thorax but not for the head. Similar to other studies (Van Emmerik et al., 2005), thorax flexion increased with gait speed in this study. Head and thorax posture did not differ between groups as might be expected based on the effect of emotion on posture in healthy individuals. When joy was felt, head and thorax postures were significantly more extended compared to sadness in healthy individuals (Roether et al., 2009; Gross et al., 2012; Crane and Gross, 2013), and these postural changes due to emotion were independent of changes in gait speed (Gross et al., 2012). In this study, head posture was more flexed in the euthymic group compared to the depressed group and healthy controls for the slow and comfortable speed conditions, and thorax posture was not different between groups for any speed conditions. These different outcomes suggest that behavioral characteristics in upper body posture may be different for mood and emotion, or between mood disorders and typical emotions. The mood phase assessed for

individuals with bipolar disorder in this study with the PHQ-9 and ASRM represents a long duration, lasting days and weeks (Altman et al., 1997; Kroenke et al., 2001). The emotions assessed in the other studies likely represent a more fleeting event, with a duration lasting seconds or minutes (Gross et al., 2010; Gross et al., 2012; Fawver et al., 2014; Kang and Gross, 2015; Kang and Gross 2016). Emotion has been described as "more displayed", "intense", "brief duration", "physiologically distinct", and mood has been described as "not displayed", "mild", "enduring duration", "physiologically not distinct" (Parkinson et al., 1996; Beedie et al., 2005). Thus, the effect of mood phase on upper body posture in this study appears to be more consistent with the descriptors for mood. That is, bodily expression of mood phase in the upper body was not as apparent as bodily expressions of emotion during gait. The differences observed in this study also suggest that future studies are needed to investigate the differential effects of emotion and mood on motor behavior in individuals with bipolar disorder and healthy controls.

For the slow and fast speed conditions, like in other studies (Ford et al., 2007; Stephenson et al., 2009), shoulder and elbow ranges of motion increased with gait speed. Wrist range of motion was limited for all speed conditions, and did not vary with gait speed. Like upper body posture, the effect of mood phase on upper extremity range of motion was not the same as the effect of emotion in healthy individuals. During gait, bodily expression of emotion in healthy individuals is manifested at the shoulder and elbow but not at the wrist (Gross et al., 2012). For example, sagittal shoulder and elbow ranges of motion were significantly greater for joy compared to sadness but wrist range of motion was similar among emotion (Gross et al., 2012). In this study, shoulder and elbow ranges of motion increased with gait speed but did not differ between groups (except shoulder range of motion between the depressed group and healthy controls at slow speed), but wrist range of motion did differ between groups for the comfortable speed condition (the

hypomanic group compared to the depressed group and healthy controls; the euthymic group compared to healthy controls). These results further confirm that the effect of mood phase in bipolar disorder differs from the effect of emotion in healthy individuals on upper extremity ranges of motion. This finding supports the idea that the phases of bipolar disorder are not simply recapitulations of typical emotional states.

As expected, lower extremity ranges of motion in this study also increased with gait speed (Öberg et al., 1994; Lelas et al., 2003). Beyond the effects of gait speed, however, mood phase also affected sagittal range of motion at the hip. Hip range of motion was greater for the hypomanic group and the euthymic group than for healthy controls for the comfortable and slow speed conditions, resulting in longer stride lengths for individuals in the hypomanic group and the euthymic group. Emotion in healthy individuals has also been reported to affect hip motion during gait. For example, hip range of motion was greater when joy was felt compared to sadness or neutral emotion (Gross et al., 2012). It was not clear in that study, however, if the difference was due entirely to emotion or to the increase in gait speed when feeling joy compared to neutral or sadness.

The effects of mood phase on center-of-mass displacement during gait occurred in both the anteroposterior and vertical directions and were highly correlated with gait speed. Even after accounting for the effects of gait speed, however, the euthymic group exhibited greater center-of-mass displacement in the anteroposterior and vertical directions compared to healthy controls. Since stride length was significantly longer for the euthymic group than healthy controls for all speed conditions even though gait speeds were similar, it is likely that the relative increase in stride length explained the differences in anteroposterior and vertical center-of-mass displacement (Gard et al., 2004; Orendurff et al., 2004; Gordon et al., 2009). Other studies have reported that

individuals with major depressive disorder had significantly lower gait speed and vertical movement compared to never-depressed individuals (Michalak et al., 2009). However, in this study anteroposterior and vertical center-of-mass displacements were not different for the depressed group compared to healthy controls, which might be due to the similar gait speed and stride length between the depressed group and healthy controls. Mean gait speed for the depressed group in this study (1.15 ± 0.28 m/s) was slightly greater than gait speed for individuals with major depressive disorder reported by Michalak et al. (2009) (1.07 ± 0.22 m/s). Since vertical center-of-mass displacement increases with gait speed (Orendurff et al., 2004), the slight difference in gait speed between studies may have accounted for similar vertical center-of-mass displacement for the depressed group observed in this study and the reduced vertical center-of-mass movement for individuals with major depressive disorder compared to healthy controls observed in the study by Michalak et al. (2009).

Consistent with other studies that have reported speed effects on normalized jerk scores (Vikne et al., 2013), normalized jerk scores for the center-of-mass in the anteroposterior and vertical directions decreased (i.e., movement smoothness increased) with gait speed for all speed conditions. After accounting for gait speed differences, however, center-of-mass movement was smoother for the depressed group than for the hypomanic group and euthymic group in the anteroposterior direction (i.e., the hypomanic group and the euthymic group for the comfortable speed condition, the hypomanic group for the slow speed condition), and less smooth for the depressed group than for healthy controls in the mediolateral direction for the comfortable speed condition but smoothness was similar in the vertical directions for all speed conditions. Since greater movement smoothness is considered to be a feature of coordinated movement (Hogan and Sternad, 2009), the results suggest that the depressed group's gait was better coordinated compared

to the hypomanic group and the euthymic group in the anteroposterior direction, but more poorly coordinated in the mediolateral direction compared to healthy controls, independent of gait speed. In contrast, bipolar disorder did not affect vertical coordination during gait in any group.

When emotion is felt in healthy individuals, center-of-mass movement during gait is smoother for joy or anger compared to sadness, and the difference in smoothness is observed only in the vertical direction (Kang and Gross, 2016). Smoother center-of-mass movement for joy or anger compared to sadness was also reported during sit-to-walk (Kang and Gross, 2015), and the difference was observed in both the anteroposterior and vertical directions. If the hypomanic and depressed phases in individuals with bipolar disorder are assumed to be similar to high arousal emotions like joy and anger, and a low arousal emotion like sadness, respectively, in healthy individuals, the effect of mood phase on center-of-mass smoothness in individuals with bipolar disorder were opposite to what might have been expected with respect to the effect of emotion on center-of-mass smoothness in healthy individuals. The opposite effects of mood phase on center-of-mass smoothness compared to emotional effects provide further evidence for the difference between mood and emotion (or mood disorder and typical emotion).

In this study, the qualitatively described high or low energy levels that are typically experienced during mania/hypomania or depression, respectively, were compared with kinetic measures, to understand how kinetic characteristics during a day-to-day task like gait might provide quantitative information about how energy is "expressed" in body movements of individuals with bipolar disorder. Like gait speed, peak values for ground reaction forces in the anteroposterior and vertical directions were higher for individuals in the hypomanic phase than other groups for the comfortable speed condition. Although peak values for ground reaction forces increase with gait speed (Keller et al., 1996; Lelas et al., 2003), higher values in the negative peak

in the anteroposterior ground reaction forces and the 1st peak in the vertical ground reaction forces for hypomanic group compared to other groups persisted even after accounting for gait speed. These results suggest that the relatively higher peaks in ground reaction forces for the hypomanic group may be related to a physical manifestation of "high energy" that individuals in manic/hypomanic bipolar disorder report (American Psychiatric Association, 2013). Although force exertion is not a direct measure of energy, it may be an indicator of the qualitative assessment of high energy that individuals in hypomanic phase are experiencing. Alternatively, these higher peaks in the ground reaction forces beyond gait speed suggest a "stomping" style of gait for hypomanic group. A body of literature indicates an association between stomping and anger (Jackman and Strober, 2003; Damon et al., 2012; Espeset et al., 2012). It may be that stomping-like gait for individuals in hypomanic phase is a bodily expression of irritability that is a behavioral characteristic for mania/hypomania (American Psychiatric Association, 2013).

As expected, peak torques and power generation at the hip, knee and ankle were highly correlated with gait speed for all speed conditions (Winter, 1983; Chen et al., 1997; Lelas et al., 2003; Orendurff et al. 2008). After accounting for gait speed, few differences between groups for peak joint torques remained (e.g., hip extensor torque was greater for the hypomanic group than for the euthymic and depressed groups in the comfortable speed condition), indicating that peak lower extremity torques for individuals with bipolar disorder were determined primarily by gait speed. Similarly, after accounting for gait speed, only one group difference in hip and knee power generation persisted (i.e., euthymic group compared to healthy controls in the comfortable speed condition). However, peak power generation at the ankle was greater for the hypomanic group than the other groups for the slow and fast speed conditions, and for the comfortable speed condition when compared to the euthymic group, even when the effect of gait speed was isolated

with the mixed model. Power (work per unit time) is a direct measure of energy, thus joint power generation during gait may be related to high or low energy that individuals with bipolar disorder experience during mania/hypomania or depression, respectively. In particular, greater ankle power generation for the hypomanic group compared to the other groups was found even after accounting for gait speed, suggesting that individuals in the hypomanic group generate excess energy for their gait speed, supporting the "increased energy" for the hypomania that is a core clinical symptom defining hypomania (American Psychiatric Association, 2013). Although increased activity/energy for mania/hypomania has been reported using related behaviors such as impulsiveness (Swann et al., 2001; Swann et al., 2003; Swann et al., 2009) measured with a self-report (Patton et al., 1995) and memory tasks matching 5-digit numbers (Dougherty et al., 2000), the assessment of power generation in this study enables a direct report of physical energy expenditure in bipolar disorder for the first time.

A limitation of this study in which the effect of mood phase in bipolar disorder on gait characteristics was investigated was the small sample size. Four hypomanic, seven euthymic and 10 depressed individuals and 14 healthy controls were included. Despite the small sample sizes, significant differences with large effect sizes for gait speed, ground reaction force and joint power generation were found between groups, especially for the hypomanic group. Assuming that the means, standard deviations and effect sizes for gait speed found in this study are representative of group differences for a larger population, a power analysis (nQuery Advisor) was performed to determine the number of participants needed for each group to achieve 90% statistical power. Because power analyses depend on standard deviations, the power analysis was performed using the standard deviation representative of hypomanic and euthymic individuals, and healthy controls groups (i.e., 0.15 m/s). Using this standard deviation value, the power analysis indicated that seven

participants were needed for each group to achieve 90% power. Thus, the study was slightly underpowered, since one of the groups had less than seven participants (hypomanic phase; n=4). Ideally, including more participants in each of the mood phase groups, and having the same number of participants in each group, would strengthen the statistical analysis and improve extrapolation to larger populations of individuals with bipolar disorder. However, the large effect sizes found in this study even with the relatively small number of participants suggest that the significant differences between mood phases are robust, and that similar differences for gait variables such as gait speed and ground reaction forces between groups will be found in a larger population of individuals with bipolar disorder.

In this study, both kinematic and kinetic measures of gait were associated with mood phase in bipolar disorder and have potential as biomarkers. Gait speed appears to be the most promising gait variable to serve as a biomarker, since it is quantitative and objective, appears to reflect disease state (i.e., mood phase), and may be acceptable to affected individuals (i.e., non-invasive, measured quickly, not much burden) (National Institute of Health Biomarkers Definitions Working Group, 2001). The hypomanic group walked faster, most of the depressed group (80%) walked slower, and the euthymic group walked at the same speed as healthy controls. In addition to gait speed, ground reaction force exerted during gait also has potential to serve as a biomarker for bipolar disorder. Since ground reaction force exerted during gait for the hypomanic group was notably excessive and greater than expected for their gait speed, measurement of ground reaction force during gait may be particularly useful to better define mania/hypomania and detect changes in mood phase into mania/hypomania. Biomechanical measures of motor behavior were sensitive to mood phase differences in bipolar disorder in this gait study, but future studies are needed to

determine whether these kinematic and kinetic measures could also serve as biomarkers for mood phase in other movements.

4.6 Conclusion

The effects of mood phase on biomechanical characteristics of gait were examined in individuals with bipolar disorder and healthy individuals. The effect of mood phase on gait characteristics was manifested primarily in gait speed and peak force and power generation in the lower body. In particular, gait characteristics for individuals in hypomanic phase were well matched with qualitative descriptions for mania/hypomania (i.e., increased motor activity, high energy) in DSM-5 criteria for bipolar disorder. How gait performance was affected by mood phase in individuals with bipolar disorder was not the same as the effect of emotion on gait in healthy individuals. Although this study was conducted in a laboratory setting, simpler assessments of gait that can be performed during a clinic visit may provide useful quantitative information about mood phase for individuals with bipolar disorder.

CHAPTER 5

DISCUSSION

5.1 Summary

The overall purpose of this dissertation was to investigate the effect of emotion and mood phase on biomechanical characteristics of body movements in healthy individuals and individuals with bipolar disorder. An interdisciplinary approach combining biomechanics for quantifying body movements and psychology for eliciting and assessing emotions was used to quantify emotional effects on sit-to-walk and movement smoothness during gait in healthy individuals. In addition, a biomechanical approach was combined with psychiatric assessment to characterize the effects of mood phase on gait in individuals with bipolar disorder and healthy individuals. Three studies were conducted to address the aims of the dissertation.

The goal of the first study (Chapter 2) was to determine if emotion changes movement pattern during sit-to-walk in healthy young adults. In previous studies, emotion had been shown to affect movement characteristics during gait and upper limb tasks, but it was not known if these effects were task-specific or could be generalized to other whole-body movements. Further, emotion is viewed as a coordinative structure for action, yet it was not known how emotion might affect coordination of a movement with subcomponent tasks like sit-to-walk. Four target emotions,

anger, joy, sadness and neutral emotion, were elicited using an autobiographical memories paradigm in healthy young individuals as they performed sit-to-walk. Key findings were that movement time to complete sit-to-walk and velocity drop in the forward direction during sit-to-walk (i.e., hesitation), decreased when anger or joy was felt compared to sadness. In addition, movement smoothness during sit-to-walk increased when anger or joy was felt compared to sadness. These findings demonstrate that the expected effects of sadness (i.e., decreased movement speed) and anger and joy (i.e., increased movement speed) are generalizable to other whole-body movement tasks. Further, study findings demonstrate the effects of emotion on movement coordination for the first time, with respect to center of mass motion (i.e., movement smoothness) and to transition between movement subcomponents (i.e., hesitation). Interestingly, the effect of emotion on movement smoothness during sit-to-walk was opposite to findings in previous work based on qualitative ratings of movement smoothness during gait (Montepare et al., 1999) and a jerk measure that was confounded by movement time and amplitude in upper limb movements (Pollick et al., 2001).

The goal of the second study (Chapter 3) was to investigate the effects of emotion on whole body coordination as assessed by movement smoothness in gait. Again, four target emotions, anger, joy, sadness and neutral emotion were elicited in healthy young individuals and were felt as they performed gait. The findings confirmed the results of the previous study (Chapter 2), that is, movement smoothness increased with anger and joy, and decreased with sadness during gait. Since smoothness is considered as a hallmark of movement coordination (Hogan and Sternad, 2009), the results of both studies suggest that emotion affects movement coordination during whole body movements. Further, the results of both studies demonstrate that emotion affects movement speed and duration, and suggest that measures used to assess movement smoothness

should account for the potential confounding effects of movement amplitude and speed. The results also suggest that observers rating movement smoothness based on observation may be assessing a different movement quality than that measured biomechanically as the normalized jerk score.

How feelings manifest in body movement may have clinical relevance for individuals with mood disorders. The aim of the third study (Chapter 4) was to identify gait characteristics associated with mood phase in bipolar disorder. Gait biomechanics were assessed for individuals with bipolar disorder in the hypomanic, euthymic, and depressed mood phases, and healthy controls when walking at self-selected slow, comfortable and fast speeds. As expected, individuals in the hypomanic phase walked faster than all other groups, but the increased ground reaction forces and joint power generation observed for these individuals were greater than predicted based on gait speed alone. Individuals in all groups changed their gait speeds relatively the same way for the slow and fast speed conditions, and few biomechanical differences between mood phases emerged for the slow and fast speed conditions. Although most of the depressed group (eight out of ten depressed individuals) walked slower than the other groups, two of the depressed individuals walked much faster than the others, and even faster than individuals in the hypomanic group. Thus, gait speed for the entire depressed group was not significantly slower than others. When the two "fast" individuals were removed from the depressed group, however, the remaining 80% of individuals in the depressed phase walked significantly slower than the other groups, as might be expected. This study is the first to quantify the effects of mood phase on body movement in individuals with bipolar disorder. This study showed that gait speed has potential to serve as a biomarker for bipolar disorder across mood phases. This study also showed that ground reaction force characteristics that cannot be captured by gait speed alone may have potential for

discriminating mood phases. Thus, findings of the study suggest that measuring biomechanical variables such as gait speed and ground reaction forces may be useful for better evaluating behavioral symptoms in bipolar disorder across mood phases, especially for the manic/hypomanic phase.

5.2 Implications

The first two studies in this dissertation investigated the effects of different emotions on movement characteristics in whole-body tasks. Outcomes of these studies were consistent with the expected effect of emotional arousal on movement speed. In the circumplex model of emotion (Posner et al., 2005), emotions are described by their location with respect to two independent axes, arousal and valence. The target emotions elicited in the first two studies were anger (high arousal and unpleasant valence), joy (high arousal and pleasant valence), sadness (low arousal and unpleasant valence) as well as neutral emotion (Fig. 5.1). Feeling the target emotions resulted in differences between high and low arousal emotions for speed-related variables during both sit-to-walk and gait (e.g., shorter durations, faster speeds, longer stride lengths, greater joint ranges of motion for higher arousal emotions). These results are consistent with what others have observed during gait initiation (Fawyer et al., 2014) and for a broader range of emotions during gait (Gross et al., 2012), but the findings extend the set of whole-body movements with demonstrated effects of emotion to include sit-to-walk. In addition, these other studies (Fawver et al., 2014; Gross et al., 2012) reported that the speed-related differences between high and low arousal emotions with the same valence (e.g., anger vs. sadness, or fear vs. sadness) were greater than between emotions with pleasant and unpleasant valences but the same arousal (e.g., anger vs. happiness, or fear vs.

happiness). Outcomes in the first two studies are consistent with the previously reported predominance of arousal over valence in bodily manifestations of emotional expression, suggesting that speed-related variables may be particularly amenable to assessment, and that valence effects may influence movement in other ways.

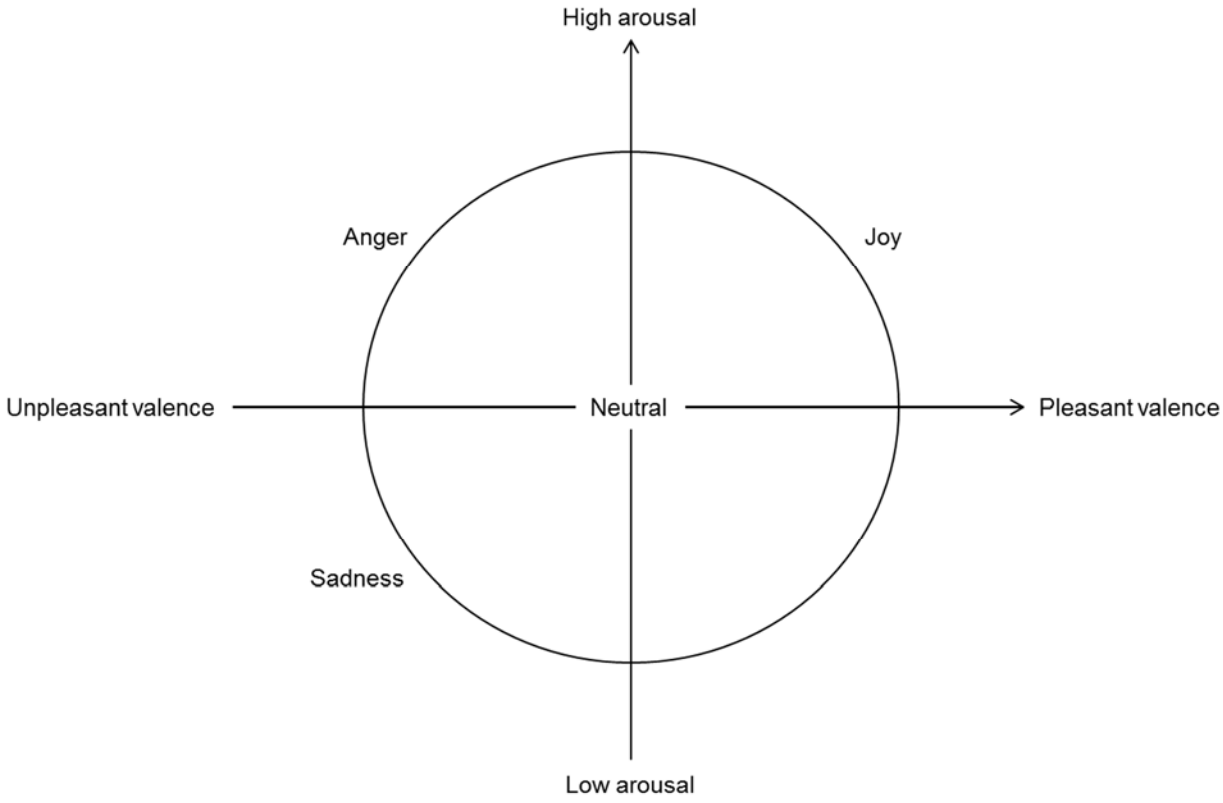

Fig. 5.1. The circumplex model of emotion. The target emotions included in these studies were joy, anger, sadness and neutral emotion. Including these emotions enabled comparisons of the effect of valence, holding arousal constant (i.e., joy vs. anger), and the effect of arousal, holding valence constant (i.e., anger vs. sadness).

Regardless of whether arousal or valence predominate in bodily expression of emotion, results from the first study showed that feeling a positive emotion like joy resulted in a pattern of movement for sit-to-walk that was faster and better coordinated than when feeling a negative

emotion like sadness. These results have clinical implications for individuals with impaired sit-to-walk, suggesting that the best assessments of sit-to-walk performance might be achieved when an individual is feeling positive rather than negative. A body of literature reported that sit-to-walk is impaired by aging and falling risks. For example, Kerr et al. (2007) reported over 100% longer sit-to-walk duration for elderly individuals at risk of falls compared to both of healthy elderly and young individuals. Buckley et al. (2009) reported 24.7 % longer sit-to-walk duration for healthy elderly individuals with no history of falls compared to healthy young individuals. Chen and Chou (2013) and Chen et al. (2013) repeatedly reported over 25.0% longer sit-to-walk duration for elderly individuals with history of falls compared to both of healthy elderly individuals with no history of falls and healthy young individuals. It was also reported that hesitation was over 55.0% greater during sit-to-walk for elderly individuals at risk of falls compared to both of healthy young and elderly individuals (Kerr et al., 2013). The results of this study showed that the effects of emotion on sit-to-walk performance can be relatively large, and have the same order of magnitude as differences in sit-to-walk performance due to aging or risk for falling reported by others. For example, differences in sit-to-walk duration and hesitation between joy and sadness were 19.0% and 44.1%, respectively. Although emotions can not change underlying biomechanical limitations, emotions can affect performance of sit-to-walk significantly, with positive emotions enhancing sit-to-walk performance and yielding better clinical assessments.

Similarly, recalling joyful memories may improve movement smoothness in individuals with jerky movements. Jerky movements have been reported for elderly individuals compared to healthy individuals during handwriting (Contreras-Vidal JL et al., 1998) and point-to-point aiming movements (Ketcham et al., 2002). Lage et al. (2003) reported individuals with bipolar disorder in euthymia had jerkier hand-drawing movements compared to healthy individuals. Caligiuri et al.

(2006) reported individuals with schizophrenia had jerkier handwriting compared to healthy individuals. If recalling joyful memories improves movement smoothness in these populations, it may be useful to consider eliciting positive emotions in a therapeutic program.

Although some qualitative studies suggest the possible effects of emotion on movement coordination (Frijda, 1987; Montepare et al., 1999; Crane and Gross, 2013), previous biomechanical studies emotion have not addressed movement coordination (Michalak et al., 2009; Roether et al., 2009; Gross et al., 2010; Naugle et al., 2010; Gélat et al., 2011; Naugle et al., 2011; Gross et al., 2012; Fawver et al., 2014). In the first two studies of this dissertation, the effects of emotion on movement coordination were assessed by measuring movement smoothness. Interestingly, the biomechanical results were completely opposite to results based on qualitative observation (Montepare et al., 1999). That is, observers reported that sad movements were smooth and angry or happy movements were jerky. Biomechanical measures that normalized for movement amplitude and time produced a different outcome, that is, sad movements were jerkier and angry and joyful movements were smoother. It may be that observers are basing their judgments of "smooth" or "jerky" on movement qualities that are time or displacement-based, or are related to movement dynamics other than jerk. Further evidence for this interpretation is provided by findings in the first two studies in which emotion arousal, with its speed-related associations, was more strongly related to movement smoothness than emotion valence, that is, smoothness differences were observed between anger and sadness, and joy and sadness, but not between anger and joy. An important implication of the apparent difference between quantitatively measured smoothness by biomechanics and subjectively judged smoothness by observers is that clinicians, who make qualitative observations when examining a patient, may not be able to accurately assess subtle quantities like movement jerk and smoothness.

The mounting evidence that emotion affects movement quantitatively suggests that biomechanical analysis may be useful when assessing the effects of a mood disorder on body movement. Based on the previous work and the outcomes of the first two studies, it was reasonable to assume that body movements may be different in individuals with elevated and irritable mood and individuals with depressed mood. The purpose of the third study was to investigate body movements in individuals with bipolar disorder in different mood phases to determine if kinematic and kinetic data might be considered as biomarkers for mood phase. Results from the third study suggest that gait characteristics can provide useful information about mood phases for individuals with bipolar disorder. The most important clinical implication of the biomechanical approach used in the study was that the high energy experienced by individuals with bipolar disorder during mania/hypomania (American Psychiatric Association, 2013) can be quantitatively demonstrated using biomechanical measures during walking. Clinically, high energy for mania/hypomania is evaluated qualitatively based on interviews (Spitzer et al., 1992; Nurnberger et al., 1994) and/or self-reports (Young et al., 1978; Altman et al., 1997). Researchers suggested characteristic behaviors such as impulsive behavior (i.e., acting before thinking) using objective laboratory tests as a quantitative symptom of mania/hypomania (Swann et al., 2001; Swann et al., 2003; Swann et al., 2009). Although impulsive behaviors are based on objective measures, they are not necessarily associated with the key clinical characteristics for mania/hypomania, "high/increased energy", but are rather associated with impaired decision making. Moreover, such characteristics can only be evaluated subjectively by self-descriptions (i.e., self-reports or clinical interviews) during a clinic visit so that impulsive behaviors in individuals with bipolar disorder could be perceived inaccurately. With the biomechanical analysis in the third study, forces and powers are directly related to energy, and the results indicated that hypomania was associated with greater force and

power generation during gait especially at the ankle. Another important finding of the study was that gait speed could be a feasible phase-specific biomarker for bipolar disorder. Individuals with hypomania walked faster, the majority of individuals with depression walked slower, and individuals with euthymia walked at the same speed as healthy controls. Although the kinematic and kinetic analysis used in this study required a motion capture system and force plates that are not typically found in a clinic, measurement of gait speed could be easily accomplished in the clinic with a gait mat and provide important, clinically relevant information about mood phase.

Another interesting finding in the third study was that the effect of mood phase on gait characteristics was not the same as the effect of emotion. Emotion affects body posture as well as spatiotemporal gait parameters. In particular, upper body motion such as shoulder and elbow ranges of motion and head and upper body posture change when emotion is felt, and changes in head and upper body posture are independent of gait speed (Gross et al., 2012). In this study, however, upper body motion was rarely affected by mood phase. In addition, emotional effects on gait variables were found in both speed-dependent (e.g., stride length) and speed-independent (e.g., head posture) variables, but the effect of mood phase on gait variables were all speed-dependent. These findings suggest that the differences in body movement patterns due to mood phase can be captured by a more limited set of biomechanical variables than that needed for characterizing emotional expression.

5.3 Limitations

There are some limitations in the studies included in this dissertation. First, in the two studies investigating the effects of emotion on body movement, only a few target emotions (anger,

joy, sadness and neutral emotion) were elicited. In previous studies that included contentment to represent a low arousal, pleasant valence emotion (Gross et al., 2012), body movement patterns with contentment were similar to neutral so contentment was not included in these studies. If contentment had been included, the study design would have allowed for investigation of the effects of positive valence across arousal levels by comparing joy with contentment and the effects of low arousal across valences by comparing sadness with contentment. Also, fear was not included in the target emotions even though the effect of fear on body movement has been investigated as a fundamental emotional state across species in other studies. According to the circumplex model, fear is an emotion with a high arousal and unpleasant valence (Posner et al., 2005). Only one target emotion was included for each quadrant, however, and anger was selected as the target emotion for the high arousal-negative valence quadrant because fear has been associated with avoidance and freezing of movement behavior.

Another limitation is that the intensities of emotional arousal and valence were not assessed separately and directly but rather the intensity with which an emotion was felt was assessed. The target emotions were selected based on the circumplex model (Posner et al., 2005), and it was assumed that the intensity with which an emotion was felt represented the intensity for both arousal and valence. Nonetheless, if arousal and valence had specifically been assessed, stronger conclusions about the separate effects of arousal and valence might have been possible.

Another limitation in the two studies of emotional expression was the lack of speed-matched trials. Speed was treated as a dependent variable, and only self-selected speed trials while feeling a target emotion were performed. Speed-independent emotional characteristics for sit-to-walk and smoothness could have been investigated if participants had performed movements in

matched-speed trials while feeling the same emotion (e.g., performing sit-to-walk while feeling sad but at the same speed of sit-to-walk trials in which the participant felt angry).

5.4 Future research

In this dissertation, the effects of emotion on body movement in healthy individuals, and the effects of mood phase on body movement in individuals with bipolar disorder and healthy controls were investigated. An important finding was that mood effects on body movement in individuals with bipolar disorder were not the same as emotion effects on body movement in healthy individuals. To determine how emotions and mood states interact in bodily expression, a future study could investigate the effect of emotion induction on body movement in individuals with mood disorders such as bipolar disorder and major depressive disorder. Since the way mood affects body movement is different than emotion, investigating the effects of emotion induction on body movement in individuals with mood disorders would be useful to understand the underlying mechanisms of the association between mood and emotion, and body movement.

Another important finding of this dissertation was that gait performance, especially gait speed and ground reaction force generation, was different between mood phases based on cross-sectional comparisons between individuals. It is not known, however, how stable the movement characteristics are for an individual within a given mood phase, or how those movement characteristics change with mood phase within an individual. To address these questions, a longitudinal study is needed to investigate the association between changes in mood phases and gait performance over a long-time period within an individual with bipolar disorder. With such a study, it would be possible to determine if characteristics of movement behavior reported in this

dissertation are variable with changes in mood phases, and are repeatable with persistence of mood phase.

In this dissertation, gait speed was identified as a potential biomarker for mood phase in bipolar disorder. To test the feasibility of gait speed as a biomarker, a full-scale research project is needed in which spatiotemporal gait parameters were measured during clinic visits in a large number of bipolar individuals. This could be done in a short time (within several minutes) using a relatively simple apparatus for real-time measurement of spatiotemporal gait parameters (GAITRite Systems; CIR Systems, INC., Franklin, NJ). Gait data could be combined with mood phase data to build the large database needed to better establish the relationship between gait speed and mood phase. In addition, this potential future study would also help clinicians to better assess motor disturbances in their patients by obtaining quantitative data during a clinic visit.

In addition, despite the same gait speed between individuals in the euthymic phase and healthy controls, the gait pattern for the euthymic individuals may not be as efficient as healthy controls because the euthymic individuals used longer and slower strides. In this dissertation, energy efficiency was not directly measured. Energy efficiency can be estimated by directly measuring mechanical energy cost by calculating positive and negative work for the lower extremity (Kuo, 2002; Gordon et al., 2009) and comparing it to the metabolic energy cost by calculating the volume of oxygen consumption and carbon dioxide production. In future studies, such analyses would enable assessment of energy inefficiency for individuals with bipolar disorder during gait.

Finally, the effect of mood phase on movement behavior in individuals with bipolar disorder was studied only for gait performance in this dissertation. It would be useful to investigate the effect of mood phase on other ordinary movement tasks. Since energy is a key clinical

characteristic of each mood phase, it would be useful to investigate a more energy-demanding task such as stair climbing to further assess the impact of mood phase on movement behavior in individuals with bipolar disorder.

REFERENCES

Altman EG, Hedeker D, Peterson JL, Davis JM. The Altman self-rating mania scale. *Biological Psychiatry* 1997; 42: 948-955.

American Psychiatric Association. The diagnostic and statistical manual of mental disorders. 5th ed. 2013. Arlington, VA.

American Psychiatric Association. Practice guideline for the treatment of patients with bipolar disorder (revision). 2002. Arlington, VA.

Andriacchi TP, Ogle JA, Galante JO. Walking speed as a basis for normal and abnormal gait measurements. *Journal of Biomechanics* 1977; 10: 261-268.

Atkinson AP, Dittrich WH, Gemmell AJ, Young AW. Emotion perception from dynamic and static body expressions in point-light and full-light displays. *Perception* 2004; 33: 717-746.

Barliya A, Omlor L, Giese MA, Berthoz A, Flash T. Expression of emotion in the kinematics of locomotion. *Experimental Brain Research* 2013; 225: 159-176.

Beedle C, Terry P, Lane A. Distinctions between emotion and mood. *Cognition and Emotion* 2005; 19: 847-878.

Bolbecker AR, Hong SL, Kent JS, Klaunig MJ, O'Donnell BF, Hetrick WP. Postural control in bipolar disorder: increased sway area and decreased dynamical complexity. *Plos One* 2011; 6: e19824.

Brach JS, McGurl D, Wert D, VanSwearingen JM, Perera S, Cham R, Studenski S. Validation of a measure of smoothness of walking. *Journal of Gerontology Series A Biological Sciences and Medical Sciences* 2010, doi: 10.1093/gerona/glq170.

Broadbent DE, Cooper PF, FitzGerald P, Parkes KR. The cognitive failures questionnaire (CFQ) and its correlates. *British Journal of Clinical Psychology* 1982; 21: 1-16.

Brodie MAD, Menz HB, Lord SR. Age-associated changes in head jerk while walking reveal altered dynamic stability in older people. *Experimental Brain Research* 2014; 232: 51-60.

Buckley T, Pitsikoulis C, Hass CJ. Dynamic postural stability during sit-to-walk transitions in Parkinson disease patients. *Movement Disorders* 2008; 23: 1274-1280.

Buckley T, Pitsikoulis C, Barthelemy E, Hass CJ. Age impairs sit-to-walk motor performance. *Journal of Biomechanics* 2009; 42: 2318-2322.

Burdick KE, Endick CJ, Goldberg JF. Assessing cognitive deficits in bipolar disorder: are self-reports valid? *Psychiatry Research* 2005; 136: 43-50.

Cabeza R, St Jacques P. Functional neuroimaging of autobiographical memory. *Trends in Cognitive Science* 2007; 11: 219-227

Caligiuri MP, Teulings HL, Filoteo JV, Song D, Lohr JB. Quantitative measurement of handwriting in the assessment of drug-induced parkinsonism. *Human Movement Science* 2006; 25: 510-522.

Cassidy F, Murry E, Forest K, Carrol BJ. Signs and symptoms of mania in pure and mixed episodes. *Journal of Affective Disorders* 1998; 50: 187-201.

Chen IH, Kuo KN, Andriacchi TP. The influence of walking speed on mechanical joint power during gait. *Gait and Posture* 1997; 6: 171-176.

Chen T, Chou LS. Altered center of mass control during sit-to-walk in elderly adults with and without history of falling. *Gait and Posture* 2013; 38: 696-701.

Chen T, Chang CC, Chou LS. Sagittal plane center of mass movement strategy and joint kinetics during sit-to-walk in elderly fallers. *Clinical Biomechanics* 2013; 28: 807-812.

Contreras-Vidal JL, Teulings HL, Stelmach GE. Elderly subjects are impaired in spatial coordination in fine motor control *Acta Psychologica* 1998; 100: 25-35.

Crane EA, Gross MM. Effort-shape characteristics of emotion-related body movement. *Journal of Nonverbal Behavior* 2013; 37: 91-105.

Darwin C. The expression of the emotions in man and animals. Oxford, UK: Oxford University Press 1872 (3rd ed. 1998).

Damon L, Matthews J, Sheehan J, Uebelacker L. Inpatient psychiatric nursing: clinical strategies & practical interventions. New York, NY: Springer Publishing Company 2012.

Dion L, Malouin F, McFadyen B, Richards CL. Assessing mobility and locomotor coordination after stroke with the rise-to-walk task. *Neurorehabilitation and Neural Repair* 2003; 17: 83-92.

Dougherty DM, Bjork JM, Marsh DM, Moeller FG. A comparison between adults with conduct disorder and normal controls on a continuous performance test: differences in impulsive response characteristics. *Psychological Record* 2000; 50: 203-219.

Draganich LF, Zacny J, Klafta J, Karrison T. The effects of antidepressants on obstructed and unobstructed gait in healthy elderly people. *Journal of Gerontology: MEDICAL SCIENCES* 2001; 56: M36-M41.

Espeset EMS, Gulliksen KS, Nordbø RHS, Skårderud F, Holte A. The link between negative emotions and eating disorder behavior in patients with anorexia nervosa. *European Eating Disorders Review* 2012; 20; 451-460.

Fawver B, Hass CJ, Park KD, Janelle CM. Autobiographically recalled emotional states impact forward gait initiation as a function of motivational direction. *Emotion* 2014; 14: 1125-1136.

Ford MP, Wagenaar RC, Newell KM. Arm constraint and walking in healthy adults. *Gait and Posture* 2007; 26: 135-141.

Frey BN, Andreazza AC, Houenou J, Jamain S, Goldstein BI, Frye MA, Leboyer M, Berk M, Malhi GS, Lopez-Jaramillo C, Taylor VH, Dodd S, Frangou S, Hall GB, Fernandes BS, Kauer-Sant'Anna M, Yatham LN, Kapczinski F, Young LT. Biomarkers in bipolar disorder: a positional paper from the International Society for Bipolar Disorders biomarkers task force. *Australian and New Zealand Journal of Psychiatry* 2013; 47: 321-332.

Frijda NH. Emotion, cognitive structure, and action tendency. *Cognition and Emotion* 1987; 1: 115-143.

Frye MA, Nassan M, Jenkins GD, Kung S, Veldic M, Palmer BA, Feeder SE, Tye SJ, Choi DS, Biernacka JM. Feasibility of investigating differential proteomic expression in depression: implications for biomarker development in mood disorders. *Translational Psychiatry* 2015; 5: e689.

Frykberg GE, Åberg AC, Halvorsen K, Borg J, Hirschfeld H. Temporal coordination of the sit-to-walk task in subjects with stroke and in controls. *Archives of Physical Medicine and Rehabilitation* 2009; 90: 1009-1017.

Gard SA, Miff SC, Kuo AD. Comparison of kinematic and kinetic methods for computing the vertical motion of the body center of mass during walking. *Human Movement Science* 2004; 22: 597-610.

Gélat T. Coudrat L, Le Pellec A. Gait initiation is affected during emotional conflict. *Neuroscience Letters* 2011; 497: 64-67.

Gordon KE, Ferris DP, Kuo AD. Metabolic and mechanical energy costs of reducing vertical center of mass movement during gait. *Archives of Physical Medicine and Rehabilitation* 2009; 90: 136-144.

Gross MM, Crane EA, Fredrickson BL. Methodology for assessing bodily expression of emotion. *Journal of Nonverbal Behavior* 2010; 34: 223-248.

Gross MM, Crane EA, Fredrickson BL. Effort-shape and kinematic assessment of bodily expression of emotion during gait. *Human Movement Science* 2012; 31: 202-221.

Hamburg MA, Collins FS. The path to personalized medicine. *New England Journal of Medicine* 2010; 363: 301-304.

Hamilton M. A rating scale for depression. *Journal of Neurology, Neurosurgery and Psychiatry* 1960; 23:56-62.

Harvey AG. Sleep and circadian rhythms in bipolar disorder: seeking synchrony, harmony, and regulation. *American Journal of Psychiatry* 2008; 165: 820-829.

Hausdorff JM, Peng CK, GoldbergerAL, Stoll AL. Gait unsteadiness and fall risk in two affective disorders: a preliminary study. *BMC Psychiatry* 2004; 4:39.

Hogan N, Sternad D. Sensitivity of smoothness measures to movement duration, amplitude, and arrests. *Journal of Motor Behavior* 2009; 41: 529-534.

Holmes EA, Bonsall MB, Hales SA, Mitchell H, Renner F, Blackwell SE, Watson P, Goodwin GM, Simplicio MD. Applications of time-series analysis to mood fluctuations in bipolar disorder to promote treatment innovation: a case series. *Translational Psychiatry* 2016; 6: e720

Jackman JM, Strober MH. Fear of feedback. *Harvard Business Review* 2003. R0304H.

Johnson KL, Gill S, Reichman V, Tassinary LG. Swagger, sway, and sexuality: judging sexual orientation from body motion and morphology. *Journal of Personality and Social Psychology* 2007; 93: 321-334.

Jones SH, Hare DJ, Evershed K. Actigraphic assessment of circadian activity and sleep patterns in bipolar disorder. *Bipolar Disorders* 2005; 7: 176-186.

Kaletch M, Pilgramm S, Bischoff M, Kindermann S., Sauerbier I, Stark R, Lis S, Gallhofer B, Sammer G, Zentgraf K, Munzert J, Lorey B. Major depressive disorder alters perception of emotional body movements. *Frontiers in Psychiatry* 2014a; 5: 4.

Kaletsch M, Krüger B, Pilgramm S, Stark R, Lis S, Gallhofer B, Zentgraf K, Munzert J, Sammer G. Borderline personality disorder is associated with lower confidence in perception of emotional body movements. *Frontiers in Psychology* 2014b; 5: 1262.

Kang GE, Gross MM. Emotional influences on sit-to-walk in healthy young adults. *Human Movement Science* 2015; 40: 341-351.

Kang GE, Gross MM. The effect of emotion on movement smoothness during gait in healthy young adults. *Journal of Biomechanics* 2016; 49: 4022-4027.

Keller TS, Weisberger AM, Ray JL, Hasan SS, Shiavi RG, Spengler DM. Relationship between vertical ground reaction force and speed during walking, slow jogging, and running. *Clinical Biomechanics* 1996; 11: 253-259.

Kerr A, Durward B, Kerr KM. Defining phases for the sit-to-walk movement. *Clinical Biomechanics* 2004; 19: 385-390.

Kerr A, Rafferty D, Kerr KM, Durward B. Timing phases of the sit-to-walk movement: validity of a clinical test. *Gait and Posture* 2007; 26: 11-16.

Kerr A, Pomeroy VP, Rowe PJ, Dall P, Rafferty D. Measuring movement fluency during the sit-to-walk task. *Gait and Posture* 2013; 37: 598-602.

Ketcham CJ, Seidler RD, Van Gemmert AWA, Stelmach GE. Age-related kinematic differences as influenced by task difficulty, target size, and movement amplitude. *Journal of Gerontology: PSYCHOLOGICAL SCIENCES* 2002; 57B: P54-P64.

Kirtley C, Whittle MW, Jefferson RJ. Influence of walking speed on gait parameters. *Journal of Biomedical Engineering* 1985; 7: 282-288.

Kroenke K, Spitzer RL, Williams JB. The PHQ-9. *Journal of General Internal Medicine* 2001; 16: 606-613.

Kuo A. Energetics of actively powered locomotion using the simplest walking model. *Journal of Biomechanical Engineering* 2002; 124: 113-120.

Kupfer DJ. The increasing medical burden in bipolar disorder. *Journal of the American Medical Association* 2005; 290: 2528-2530.

Lage GM, Malloy-Diniz LF, Neves FS, Gallo LG, Valentini AS, Corrêa H. A kinematic analysis of manual aiming control on euthymic bipolar disorder. *Psychiatry Research* 2013; 208: 140-144.

Lelas JL, Merriman GJ, Riley PO, Kerrigan DC. Predicting peak kinematic and kinetic parameters from gait speed. *Gait and Posture* 2003; 17: 106-112.

Lemke M, Wendorff T, Mieth B, Buhl K, Linnemann M. Spatiotemporal gait patterns during over ground locomotion in major depression compared with healthy controls. *Journal of Psychiatric Research* 2000; 34: 277-283.

Lohr JB, Caligiuri MP. Abnormalities in motor physiology in bipolar disorder. *Journal of Neuropsychiatry and Clinical Neuroscience* 2006; 18: 342-349.

Magnan A, McFadyen BK, St-Vincent G. Modification of the sit-to-stand task with the addition of gait initiation. *Gait and Posture* 1996; 4: 232-241.

Martínez-Arán A, Vieta E, Colom F, Torrent C, Reinares M, Goikolea JM, Benabarre A, Comes M, Sánchez-Moreno J. Do cognitive complaints in euthymic bipolar patients reflect objective cognitive impairment? *Psychotherapy and Psychosomatics* 2006; 74: 295-302

Menz HB, Lord SR, Fitzpatrick RC. Acceleration patterns of the head and pelvis when walking on level and irregular surfaces. *Gait and Posture* 2003; 18: 35-46.

Merikangas KR, Akiskal HS, Angst J, Greenberg PE, Hirschfeld RMA, Petukhova M, Kessler RC. Lifetime and 12-month prevalence of bipolar spectrum disorder in the national comorbidity survey replication. *Archives of General Psychiatry* 2007; 64: 543-552.

Michalak J, Troje NF, Fischer J, Vollmar P, Heidenreich T, Schulte D. Embodiment of sadness and depression gait patterns associated with dysphoric mood. *Psychosomatic Medicine* 2009; 71: 580-587.

Minassian A, Henry BL, Geyer MA, Paulus MP, Young JW, Perry W. The quantitative assessment of motor activity in mania and schizophrenia. *Journal of Affective Disorders* 2010; 210: 200-206.

Montepare JM, Goldstein SB, Clausen A. The identification of emotions from gait information. *Journal of Nonverbal Behavior* 1987; 11: 33-42.

Montepare J, Koff E, Azitchik D, Albert M. The use of body movements and gestures as cues to emotions in younger and older adults. *Journal of Nonverbal Behavior* 1999; 23: 133-152.

Murray PM, Kory RC, Sepic SB. Walking patterns of normal women. *Archives of Physical Medicine and Rehabilitation* 1970; 51: 637-650.

National Institute of Health Biomarkers Definitions Working Group. Biomarkers and surrogate endpoints: preferred definitions and conceptual framework. *Clinical Pharmacology and Therapeutics* 2001; 69: 89-95.

National Institute of Mental Health. Bipolar disorder. Retrieved April 2016 from https://www.nimh.nih.gov/site-info/citing-nimh-information-and-publications.shtml.

Naugle KM, Hass CJ, Joyner J, Coombes SA, Janelle CM. Emotional state affects the initiation of forward gait. *Emotion* 2011; 11: 267-277.

Naugle KM, Joyner J, Hass CJ, Janelle CM. Emotional influences on locomotor behavior. *Journal of Biomechanics* 2010; 43: 3099-3103.

Nurnberger JR JI, Blehar MC, Kaufmann CA, York-Cooler C, Simpson SG, Harkavy-Friedman J, Severe JB, Malaspina D, Reich T. Diagnostic interview for genetic studies. Rational, unique features, and training. *Archives of General Psychiatry* 1994; 51: 849-859.

Öberg T, Karsznia A, Öberg K. Joint angle parameters in gait: reference data for normal subjects, 10-79 years of age. *Journal of Rehabilitation Research and Development* 1994; 31: 199-213.

Orendurff MS, Bernatz GC, Schoen JA, Klute GK. Kinetic mechanisms to alter walking speed. *Gait and Posture* 2008; 27: 603-610.

Orendurff MS, Segal AD, Klute GK, Berge JS, Rohr ES, Kadel NJ. The effect of walking speed on center of mass displacement. *Journal of Rehabilitation Research and Development* 2004; 41: 829-834.

Paleacu D, Shutzman A, Giladi N, Herman T, Simon ES, Hausdorff JM. Effects of pharmacological therapy on gait and cognitive function in depressed patients. *Clinical Neuropharmacology* 2007; 30: 63-71.

Parkinson B, Totterdell P, Driner RB, Reynolds S. Changing moods: the psychology of mood and mood regulation. Harlow, UK: Addison Wesley Longman 1996.

Patton JH, Stanford MS, Barratt ES. Factor structure of the Barratt impulsiveness scale. *Journal of Clinical Psychology* 1995; 51: 768-774.

Peele PB, Xu Y, Kupfer DJ. Insurance expenditures on bipolar disorder: clinical and parity implications. *American Journal of Psychiatry* 2003; 160: 1286-1290.

Plante DT, Winkelman JW. Sleep disturbance in bipolar disorder: therapeutic implications. *American Journal of Psychiatry* 2008; 165: 830-843.

Pollick FE, Paterson HM, Brudelin A, Sanford AJ. Perceiving affect from arm movement. *Cognition* 2001; 82: B51-B61.

Posner J, Russel JA, Peterson BS. The circumplex model of affect: an integrative approach to affective neuroscience, cognitive development, and psychopathology. *Development and Psychopathology* 2005; 17: 715-734.

Pozzo T, Berthorz A, Lefort L. Head stabilization during various locomotor tasks in humans. I. Normal subjects. *Experimental Brain Research* 1990; 82: 97-106.

Roether CL, Omlor L, Christensen A, Giese MA. Critical features for the perception of emotion from gait. *Journal of Vision* 2009; 9: 1-32.

Rohrer B, Fasoli S, Krebs HI, Hughes R, Volpe B, Frontera WR, Stein J, Hogan N. Movement smoothness changes during stroke recovery. *Journal of Neuroscience* 2002; 22: 8297-8304.

Rottenberg J. Mood and emotion in major depression. *Current Directions in Psychological Science* 2005; 14: 167-170.

Rottenberg J, Gross JJ. When emotion goes wrong: realizing the promise of affective science. *Clinical Psychology Science and Practice* 2003; 10: 227-232.

Rush AJ, Trivedi MH, Ibrahim HM, Carmody TJ, Arnow B, Klein DN, Markowitz JC, Ninan PT, Kornstein S, Manber R, Thase ME, Kocsis JH, Keller MB. The 16-item quick inventory of depressive symptomatology (QIDS), clinician rating (QIDS-C), and self-report (QIDS-SR): a psychometric evaluation in patients with chronic major depression. *Biological Psychiatry* 2003; 54: 573-583.

Russell JA. A circumplex model of affect. *Journal of Personality and Social Psychology* 1980; 39: 1161-1178.

Seidler RD, Alberts JL, Stelmach GE. Multijoint movement control in Parkinson's disease. *Experimental Brain Research* 2001; 140: 335-344.

Smith MA, Brandt J, Shadmehr R. Motor disorder in Huntington's disease begins as a dysfunction in error feedback control. *Nature* 2000; 403: 544-549.

Spitzer RL, Williams JBW, Gibbon M, First MB. The structured clinical interview for DSM-III-R (SCID), I: history, rationale, and description. *Archives of General Psychiatry* 1992; 49: 624-629.

Stensdotter A, Pedersen N, Wanvik A, Öhberg F, Fløvig JC, Fors EA. Upper body 3-dimensional kinematics during gait in psychotic patients: a pilot-study. *Experimental Brain Research* 2012; 221: 393-401.

Stensdotter A, Lorås HW, Fløvig JC, Djupsjöbacka M. Postural control in quiet standing in patients with psychotic disorders. *Gait and Posture* 2013; 38: 918-922.

Stephenson JL, Lamontagne A, De Serres SJ. The coordination of upper and lower limb movements during gait in healthy and stroke individuals. *Gait and Posture* 2009; 29: 11-16.

Stins JF, van Gelder LMA, Oudenhoven LM, Beek PJ. Biomechanical organization of gait initiation depends on the timing of affective processing. *Gait and Posture* 2015; 41: 159-163.

Stroop JR. Studies of interference in serial verbal reactions. Journal of Experimental Psychology 1935; 18: 643-662.

Svoboda E, McKinnon MC, Levine B. The functional neuroanatomy of autobiographical memory: a meta-analysis. *Neuropsychologia* 2006; 44: 2189-2208.

Swann AC, Anderson JC, Dougherty DM, Moeller FG. Measurement of inter-episode impulsivity in bipolar disorder. *Psychiatry Research* 2001; 101: 195-197.

Swann AC, Pazzaglia P, Nicholls A, Dougherty DM, Moeller FG. Impulsivity and phase of illness in bipolar disorder. *Journal of Affective Disorders* 2003; 73: 105-111.

Swann AC, Lijffijt M, Lane SD, Steinberg JL, Moeller FG. Increased trait-like impulsivity and course of illness in bipolar disorder. *Bipolar Disorders* 2009; 11: 280-288.

Torres IJ, Boudreau VG, Yatham LN. Neuropsychological functioning in euthymic bipolar disorder: a meta-analysis. *Acta Psychiatrica Scandinavica* 2007; 116: 17-26.

Van Emmerik REA, McDermott WJ, Haddad JM, Van Wegen EEH. Age-related changes in upper body adaptation to walking speed in human locomotion. *Gait and Posture* 2005; 22: 233-239.

Vikne H, Bakke ES, Liestøl, Sandbæk G, Vøllestad N. The smoothness of unconstrained head movements is velocity-dependent. *Human Movement Science* 2013; 32: 540-554.

Wallbott HG. Bodily expression of emotion. *European Journal of Social Psychology* 1998; 28: 879-896.

Wallbott HG, Scherer KR. Cues and channels in emotion recognition. *Journal of Personality and Social Psychology* 1986; 51: 690-699.

White DK, Neogi T, Zhang Y, Niu J, Katz PP. Association of slow gait speed with trajectories of worsening depressive symptoms in knee osteoarthritis: an observational study. *Arthritis Care and Research* 2016; 69: 209-215.

Winter DA. Energy generation and absorption at ankle and knee during fast, natural, and slow cadences. *Clinical Orthopaedics and Related Research* 1983; 175: 147-154.

World Health Organization. The global burden of disease: 2004 update. 2010. Geneva, Switzerland.

Yogev-Seligmann G, Giladi N, Gruendlinger L, Hausdorff JM. The contribution of postural control and bilateral coordination to the impact of dual tasking on gait. *Experimental Brain Research* 2013; 226: 81-93.

Young RC, Biggs JT, Ziegler VE, Meyer DA. A rating scale for mania: reliability, validity and sensitivity. *British Journal of Psychiatry* 1978; 133: 429-435.

Zeni Jr JA, Richards JG, Higginson JS. Two simple methods for determining gait events during treadmill and overground walking using kinematic data. *Gait and Posture* 2008; 27: 710-714.