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Expression of Emotion in the Kinematics of Locomotion

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Abstract Here we examine how different emotions - happiness, fear, sadness and anger - affect the kinematics of locomotion. We focus on a compact representation of locomotion properties using the intersegmental law of coordination (Borghese et al 1996), which states that, during the gait cycle of human locomotion, the elevation angles of the thigh, shank and foot do not evolve independently of each other but form a planar pattern of co-variation. This phenomenon is highly robust and has been extensively studied. The orientation of the plane has been correlated with changes in the speed of locomotion and with reduction of energy expenditure as speed increases. An analytical model explaining the conditions underlying the emergence of this plane and predicting its orientation reveals that it suffices to examine the amplitudes of the elevation angles of the different segments along with the phase shifts between them (Barliya et al 2009). We thus investigated the influence of different emotions on the parameters directly determining the orientation of the intersegmental plane and on the angular rotation profiles of the leg segments, examining both the effect of changes in walking speed and effects independent of speed. Subjects were professional actors and naïve subjects with no training in acting. As expected, emotions were found to strongly affect the kinematics of locomotion, particularly walking speed. The intersegmental coordination patterns revealed that emotional expression caused additional modifications to the locomotion patterns that could not be explained solely by a change in speed. For all emotions except sadness the amplitude of thigh elevation angles changed from those in neutral locomotion. The intersegmental plane was also differently oriented, especially during anger. We suggest that, while speed is the dominant variable allowing discrimination between different emotional gaits, emotion can be reliably recognized in locomotion only when speed is considered together with these other kinematic changes.

Keywords Emotion · Locomotion · Intersegmental coordination

1 Introduction

The first modern scientific study of human emotion was René Descartes' "Emotions" (Descrates 1649) in which Descartes methodologically described all possible emotions. Emotions may be viewed as psychological states directly resulting from physiological activities and manifested in all aspects of human behavior. Emotions affect facial expressions, tone of voice, body expression, gestures and locomotion and a variety of physiological parameters. Day-to-day situations continually require social judgments on the emotional state of other individuals. When people are viewed at a distance or their faces are not easily visible or their voices cannot be heard, such judgments must largely rely on information from body movement, such as gait (Montepare et al 1987). Indeed, humans can recognize expression of emotion even from impoverished stimuli, such as point-light displays following natural arm movements (Pollick et al 2001b). Even in more complex movements, such as stylized dancing, subjects were able to recognize one of six portrayed emotions considerably above chance levels (Dittrich et al 1996; Walk and Homan 1984).

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As dynamic point light or full light displays are always better recognized than static displays (Atkinson et al 2004), there appear to be differences in the characteristic kinematic patterns of the movements. Giese and Poggio (2000) used linear combinations of trajectories to show that classes of complex movements can be approximated by linear combinations of a small number of prototypical trajectories. Similar approaches have been developed in computer graphics to approximate new movements by interpolation (Bruderlin and Williams 1995; Unuma et al 1995) and in computer vision (Yacoob and Black 1999). Troje (2002) was similarly able to capture the essence of locomotion in a reduced space and to synthesize artificial point-light walking figures whose gender was correctly recognized. As data based on a linearization of motion can be used for gender classification, Troje proposed that other attributes like emotional states can be similarly treated.

The most prominent kinematic difference ascribed to movements produced under different emotional conditions is speed of body movement (Paterson et al 2001; Sawada et al 2003); gait speed and cycle duration are also affected (Cluss 2006). For arm movements, velocity, acceleration and movement jerkiness are associated with emotional arousal (Pollick et al 2001b), as are timing and spatial amplitude (range) (Amaya et al 1996), which also affect classification accuracy (Atkinson et al 2004).

Examining both clinical patients and lay actors, Michalak et al (2009) investigated gait patterns associated with depression and sadness, using music to induce specific emotions. Both the patients and lay actors who were experiencing sadness converged to similar gait patterns with slower gait speed. Naugle et al (2010) showed that viewing pleasant pictures during forward locomotion elicited approach behavior, and enhancing step velocity, whereas unpleasant pictures elicited avoidance behavior leading to shorter and slower steps. The different gait velocities during different emotions affect the range of joint motion (Gross et al 2011). Body postures during walking also differed during different emotions but did not correspond to differences in walking speed. Identifying critical features for the perception of emotion during locomotion, Roether et al (2009) concluded that, in terms of body configuration and movement kinematics, some features specific to certain emotions cannot be explained solely by variations in speed. These features included changes in the amplitudes of movement of particular limb segments and joints. Furthermore, Hicheur et al (Unpublished) observed that the head and trunk orientations differ across emotions, and that these parameters, together with speed, are essential for correct identification of different emotions.

Thus, speed of body movements is largely determined by the experienced emotion. It is clear that gait speed affects kinematic parameters (e.g., joint amplitudes). Therefore, it remains to determine what effects different emotions have on different body configurations and kinematic characteristics of locomotion beyond those due to changes in speed. Roether et al (2009) significant findings were mainly related to the amplitudes of individual joints angles at the level of arms and upper-body. Here we study the effects of different emotions on the lower limbs and on the intersegmental coordination between different leg segments.

We base our study on the most robust principle of coordination in human locomotion discovered to date, the *law of intersegmental coordination* (Borghese et al 1996). This law asserts that during locomotion the elevation angles of the thigh, shank and foot, expressed with respect to the direction of gravity which is associated with an extrinsic frame of reference, do not evolve independently of each other. Instead they co-vary along a plane and the pattern of covariation is a closed curve reminiscent of a teardrop (Borghese et al 1996). The orientation of this plane is correlated with the **speed** of locomotion and it rotates so as to reduce the energy expenditure associated with increasing speed (Bianchi et al 1998). Many studies have focused on the law of intersegmental coordination as evidence for central control, showing its appearance in many types of locomotion (see Cheron et al (2001), Courtine and Schiepati (2004), Ivanenko et al (2005b), Ivanenko et al (2005a), Ivanenko et al (2008) and more).

To account for the geometric and temporal characteristics of the intersegmental law of coordination, Barliya et al (2009) modeled the angular rotations of the elevation angles of each of the three leg segments (thigh, shank and foot) using simple sinusoids, thus enabling an an analytical description of the properties of this plane in terms of the amplitudes (ranges of motion), frequencies and phases of these angular rotations. It was shown that the planarity effect can only emerge when the frequencies of the elevation angles are either all equal or, if only two of them are equal, the corresponding phases are also equal.

The model confirms that changes in the orientation of the plane of intersegmental coordination are strongly correlated with changes in the phase shifts between the rotations of the different leg segments (Bianchi et al 1998).

The model thus provides us with a reliable tool for studying the influence of different emotions on the kinematic parameters underlying the law of intersegmental coordination. To investigate the effects of emotion on these parameters, we have developed a method for distinguishing effects due to speed alone from those stemming from the underlying emotion. Additionally, since the model was found to be predictive of the orientation of the plane for neutral locomotion, we tested its predictability during induced emotional locomotion. If the same model can predict the orientation of the plane under different emotional conditions we can say that similar considerations to those pertaining to neutral locomotion also pertain to emotional conditions. That is, the kinematic effects on the orientation of the plane are quite similar, irrespective of whether speed or emotion cause the change in kinematics and body configuration. Importantly, the characteristics of the plane express a link between kinematics and energy expenditure (Bianchi et al 1998).

The investigation of the effect of emotion on gait should be seen in the context of the current leading theories of emotion. On the one hand, *discrete models* of emotion suggest the existence of a limited number of basic emotions, with emotional reactions considered to be "implemented" by dedicated neural circuits and neuromotor programs (Scherer 2000). According to this view, each basic emotion is thought to emerge from an independent neural system. In contrast, another approach suggests the existence of a graded continuous two dimensional emotion space. This so-called circumplex model proposed by Posner et al (2005) assumes the existence of two orthogonal dimensions, valence (pleasantness) and arousal (activation), that are needed to span the emotion space. Each emotion is understood to be represented as a linear combination of these two dimensions, with varying degrees of both valence and arousal. Unlike in the discrete view, all affective states arise from the activation of common, overlapping neurophysiological systems.

We were able to conduct this study on two groups of subjects and compare their performances: naïve subjects (university students) and professional actors who are very experienced in expressing and conveying emotions. In previous studies, despite large differences in the abilities of professional actors to express emotion, the differences observed among emotions remained stable (Wallbott 1998). Numerous studies also confirmed that naïve actors can successfully convey emotion. We therefore investigated whether the naïve subjects differ in some level from professional actors.
To conclude, the aim of this work is to study:

1. How emotion affects the most robust law of locomotion, the intersegmental law of coordination. Is planarity affected or does it break down?
2. How is the orientation of the plane affected by emotion and how does it reflect changes in the kinematic parameters characterizing rotations of limb segments, viz., movement amplitudes and phase shifts between the rotations of the different segments.
3. The orientation of the plane is expected to change according to the changes in speed associated with the various emotions. This is due to the strong influence of speed on the kinematic parameters of the leg segments movements. However, given the reasonable assumption that there are effects of emotion that cannot be explained by speed alone, what are these effects and do they support either of the discrete versus continuous (circumplex) emotion theories?

2 Materials and Methods

2.1 Subjects

Thirteen naïve subjects (university students, male and female, average age 27 years) were recorded in the motor control laboratory in Tübingen Germany (Group I). Group II consisted of 8 professional actors (male and female, average age 27 years) from Ecole Jacques Lecocq, Paris, France recorded at the Ecole de France. All research with human subjects was approved by the local ethics boards of the Tübingen University and conformed to the principles of the Helsinki declaration.

2.2 Experimental setup and procedures

Kinematic data were recorded at 120 Hz by a VICON 612 motion capture system (Vicon Motion System Ltd., Oxford, UK). Forty-one markers were placed on the subjects' body and legs according to the marker placement protocol for the Plug-in-Gait Marker Placement of Lifemodeler (Marker Placement Protocols). The markers were positioned with a spatial accuracy of about 1mm and calibration procedures ensured that all the recorded position errors were below 1.2mm. Markers on the leg were located at the: anterior superior iliac spine (ASIS), lower lateral 1/3 of the thigh, just below the swinging hand at its lowest position (THI), the lateral epicondyle of the knee (KNE), lateral malleoulus of the ankle (ANK) and the second metatarsal head, on the mid-foot side of the equinus break between forefoot and mid-foot (TOE). The remaining markers were located on the upper body.
Subjects were recorded walking along a straight line for about 5 meters while expressing different types of emotions: neutral condition, anger, fear, joy and sadness. With the naïve subjects at the university of Tübingen we followed Roether et al (2009) method for inducing emotion. Briefly, the subjects were instructed to recall a past situation associated with the relevant emotion.

Furthermore, they were asked to express this emotion with gestures, vocalization and facial expressions. They were instructed to continue until they started to experience the emotion. To validate the quality of the emotional walking, psychophysical experiments were conducted showing that the majority of the recorded movements were categorized as expressing the emotion that the subject was intending to express. Similar methods were used to obtain the motion data recorded at the Ecole de France. The procedure has been found to be effective in producing both positive and negative moods by a meta-analysis which analyzed 250 mood induction procedures in 111 studies (Westermann et al 1996). More recently, Gross et al (2011) confirmed that the recall paradigm can induce emotion in untrained subjects. They found that these emotions are actually experienced by the subjects and are well encoded in their body movements. We did not instruct the subjects to walk at a certain speed. Since different emotional conditions affect locomotion speed, we carried out speed matching trials where subjects in the neutral condition walked at slow and fast speeds that spanned the range usually associated with the different emotions.

2.3 Data Analysis

Geometric variables. The leg was modeled as an interconnected chain of rigid segments similar to the model used by Borghese et al (1996). The three segments of the leg, thigh, shank and foot were defined by the pair of markers, THI-KNE, KNE-ANK and ANK-TOE, respectively. The main axis of the limb was defined as the segment between the hip and ankle. The elevation angle of a limb segment was defined as the orientation of the segment with respect to the vertical axis and the walking direction, being positive in the forward direction. Elevation angles were computed in the sagittal plane only, as those in the frontal plane are negligible (Bianchi et al 1998). The elevation angle for a segment i in the sagittal plane is defined as:

$$\theta_i = \arctan\left(\frac{x_d - x_p}{z_p - z_d}\right) \tag{1}$$

where d and p denote the distal and proximal endpoints of the segment, respectively. We also derived the relative joint angles between two adjacent limb segments, as defined in Borghese et al (1996), as follows:

$$\gamma_i = \arccos\left(\sum_{k=1}^{3} a_k b_k\right) \tag{2}$$

where a_k and b_k denote the h^{th} direction cosine of segment i and segment *i+1*, respectively. These angles are shown in Figure 1.

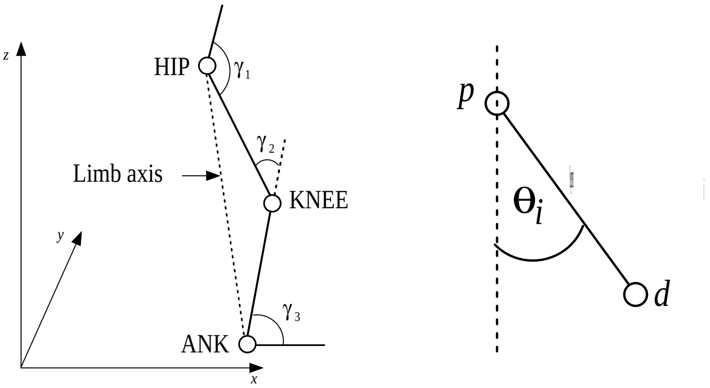


Fig. 1: Geometric variables: Left, the 3D relative angles (γ_i) between two adjacent segments. Right, the elevation angles measured between a segment and the vertical, with p and d denoting the proximal and distal points on the limb segment.

Gait cycle. By convention the human gait cycle begins when one of the feet makes contact with the ground and ends when the same foot contacts the ground again (Vaughan et al 1999). Three gait cycles were extracted for each emotion for each of the subjects in Group I, and a variable number for Group II. The timing of the gait cycle was normalized with respect to its duration to permit comparisons between gaits with different speeds. Gait cycle time (T) was measured as the time interval between the zero crossings of the angular velocity of the elevation angles of the limb axis (Borghese et al 1996; Bianchi et al 1998). These points denote the extrema of the elevation angle which, in turn, mark the *toe-off* and *heel-down* phases.

Fourier Decomposition. The first two Fourier harmonics have been shown to account for $\sim 98\%$ of the experimental variance of the thigh, shank and foot angles obtained for each trial (Bianchi et al 1998). In addition, the elevation angle waveforms tend to become progressively more sinusoidal with increasing speed as is evident from the increase of percentage variance (PV) of the 1^{st} harmonic (Ivanenko et al 2002). We have therefore fitted the time course of each of the elevation angles and expressed them as the sum of the three first harmonics of the Fourier series as follows:

$$\theta_i(t) = a_{0i} + \sum_{j=1}^{3} a_{ji}\cos(j\omega_i t) + b_{ji}\sin(j\omega_i t) \tag{3}$$

The differences between the segments are characterized by the coefficients $\{a_{0i}, a_{ji}, b_{ji}\}$ $(j = 1..3)$ and the fundamental frequency ω_i. A non linear least-squares method was used to find the coefficients and the fundamental frequency for each segment.

It is more useful and more intuitively meaningful to interpret the intersegmental relation if the set of equations of the form (3) are written in terms of amplitudes and phases of sinusoids. The identity

$$a\cos(x) + b\sin(x) = A\sin(x + \varphi) \tag{4}$$

where,

$$A = \sqrt{a^2 + b^2} \quad \text{and} \quad \varphi = \arctan\left(\frac{b}{a}\right) \tag{5}$$

relates the Fourier coefficients in equation 3 to the amplitude A and the phase φ of the relevant harmonic. Applying identity (4) to the time course representation of the elevation angles (3) we obtain:

$$\theta_i(t) = a_{0i} + \sum_{j=1}^{3} A_{ji}\sin(j\omega_i t + \varphi_{ji}) \tag{6}$$

The "energy" of a harmonic may be defined by the relative magnitude of its amplitude compared to those of all three harmonics. Thus, the "energy" contained within harmonic i is: $A_i/(A_1 + A_2 + A_3)$

Intersegmental Coordination. The patterns of intersegmental coordination of each limb in the sagittal plane were described by the temporal covariation among the elevation angles of the thigh, shank, and foot segments. When these angles are plotted one versus the others in a three-dimensional plot, they describe a path that can be fitted by a plane over each gait cycle. Principal component analysis (PCA) was used to quantify the spatiotemporal structure of the intersegmental coordination of the body segments. The variance in the data accounted for by each principal component is expressed by its percentage variance (PV) and given by

$$PV_i = 100 \times \frac{\lambda_i}{\sum_{j=1}^{3}\lambda_j}$$

where λ_i is the variance measure (the eigenvalue corresponding to the i-th PC) in the direction of the i-th PC.

The number of components required to account for the data variance provides insight into the number of degrees of freedom (DOFs) of the legs during locomotion. Particularly planar covariation among limb segments in the angular space can quantify the strength of the intersegmental coupling. For planar covariation the percentage variance should fulfill $PV_1 \geq PV_2 \gg PV_3$ and $PV_3 \ll 1$. For a perfect plane PV_3 would be exactly zero. Since the data were noisy and a complete planar covariation could not be achieved, we adopted the criterion of $PV_3 \leq 1\%$ used previously (Borghese et al 1996; Bianchi et al 1998). Thus the first two vectors lay on the best fitting plane, whereas the third vector was the normal to the plane which also defined its orientation. Finally, for neutral locomotion, the orientation of the plane is predicted to be given by (Barliya et al 2009):

$$n = \begin{pmatrix} -A_2A_3\sin(\varphi_2 - \varphi_3) \\ A_1A_3\sin(\varphi_1 - \varphi_3) \\ -A_1A_2\sin(\varphi_1 - \varphi_2) \end{pmatrix} \tag{7}$$

where A_1, A_2 and A_3 are the amplitudes of the first harmonics (see fourier decomposition above) of the thigh, shank and foot, respectively. Similarly, φ_1, φ_2 and φ_3 are the respective phases. The elements of the normal to the plane correspond to the direction cosines with the positive semi-axis of the thigh, shank, and foot angular coordinates. The model provides an expression for the orientation of the plane. However, using a model in which the movement of each segment is represented by a simple sinusoidal function Barliya et al (2009) also derived the following conditions for the emergence of the plane during human locomotion:

1. $\omega_1 = \omega_2 = \omega_3$, or
2. $\omega_1 = \omega_2 \neq \omega_3$ and $\varphi_1 = \varphi_2$

where ω_i is the fundamental frequency of the sinusoid corresponding to the thigh, shank and foot, respectively ($i = 1 \ldots 3$). For the second condition, the subscripts were arbitrarily chosen here, and it holds for any choice of a pair of equal frequencies.

2.4 Statistical Analysis

We performed a three-way ANOVA with subject group (Group I or Group II) serving as a *between*-subject factor. Emotion and either body part, frequency ratios (between the segments), and phase shift type or orientation error served as *within*- subject factors. Mauchly's tests of sphericity for validating the repeated measure ANOVA were performed and Greenhouse-Geisser corrections were applied wherever necessary.

To study the effects of different emotions on kinematic parameters, beyond change in speed, a linear regression between gait speed and the various kinematic parameters was performed during neutral walking. The slopes of the regression lines denoted the rate of change of the examined parameter with change in speed. If, during emotional walking, a parameter was affected by factors other than speed alone, there should be a change in slope.

The test was conducted as follows (Fisher 1921): Let the slopes of two different regression analyses be a_1 and a_2. The test statistic was Student's t test, computed as the difference between the two slopes divided by the standard error of the difference between the slopes, that is,

$t = \frac{a_1 - a_2}{s_{b_1 - b_2}}$ on $(N-4)$ degrees of freedom. The standard error of the difference is given by $s_{a_1-a_2} = \sqrt{s^2_{a_1} + s^2_{a_2}}$.

3 Results

To achieve a clearer and more concise notation, A_j $(j = 1..3)$ was used to designate the amplitude of the j^{th} harmonic of a specific segment (thigh, shank or foot). By contrast, phases (φ_i) and frequencies (ω_i) where $i = 1..3$ always related to the phases and frequencies of the first harmonics of the thigh $(i = 1)$, shank $(i = 2)$ and foot $(i = 3)$, respectively.

3.1 ”Energy” of the 1^{st} harmonic: $\frac{A_1}{A_1+A_2+A_3}$

To examine the differences in the amount of energy contained within the different harmonics across the different emotions, body segments and subject group, we performed a three-way ANOVA with subject group as a between-subject factor and emotion and leg segment serving as within-subject factors We found a main effect for group, emotions and body parts ($F = 12.42$; $p < 0.01$, $F = 3.81$; $p < 0.05$ and $F = 54.15$; $p < 0.001$, respectively). The three-way interaction emotions × body parts × group was statistically significant ($F = 4.48$; $p < 0.001$). The two-way interactions body parts × group and emotions × body parts were also significant ($F = 22.8$; $p < 0.001$ and $F = 14.45$; $p < 0.001$, respectively). However, the two-way interaction emotions × group was not significant. Fig. 2 clearly shows that the ”energy” of the amplitude of the first harmonic was highest for the thigh and lowest for the foot for all emotions. To further analyze the effect of emotion on the energy parameter we conducted two-way ANOVAs between the groups and emotions for each of the leg segments. The energies with respect to each segment across emotions are presented in Figure 3. The movements of the thigh were most affected by emotion ($F = 16.77$; $p < 0.0001$). However, both the factor 'group' and the interaction emotion × group were not significant (Figure 3a). The shank segment showed no effect for 'group' but 'emotion' showed a significant effect ($F = 11.74$; $p < 0.0001$), as did the interaction emotion × group ($F = 6$; $p < 0.0001$) (Figure 3b). The foot showed a main effect for both 'emotion' and 'group' ($F = 23.03$; $p < 0.0001$ and $F = 25.05$; $p < 0.0001$, respectively) (Figure 3c).

Thus, emotion consistently affected the energy measure, although the 'group' factor did not necessarily affect the kinematics of locomotion as assessed by the energy measure.

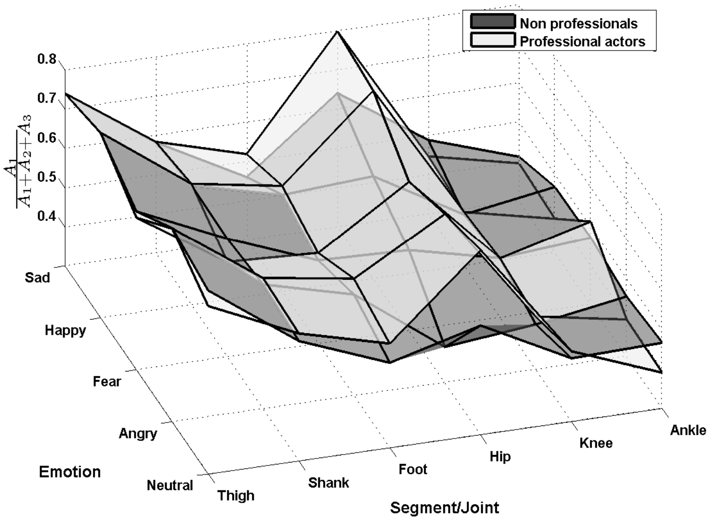
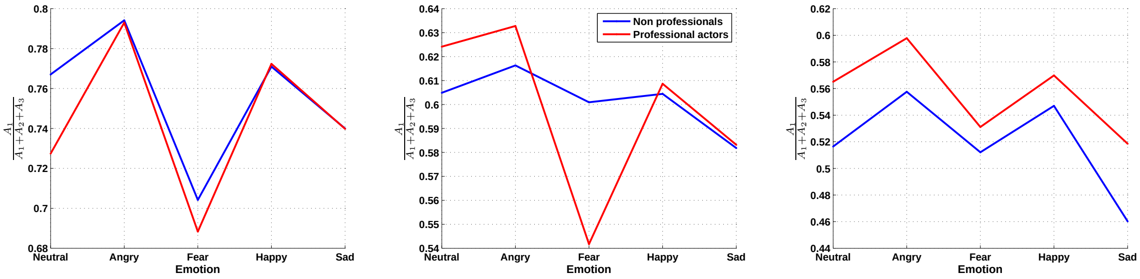


Fig. 2: Average energy in the first harmonic for the various emotions. The dark mesh represents the naive subject group and the light mesh the professional actors.

3.2 Ratio of the amplitudes of the 1^{st} and 2^{nd} harmonics: $\frac{A_1}{A_2}$

The statistical model for analyzing the ratio of 1^{st} to 2^{nd} harmonics was the same as that used above, the three-way ANOVA with 'subject group' as a between-subject factor, and 'emotion' and leg segments serving as within-subject factors. The ratio of the amplitudes of the first and second harmonics (which can serve as a further indicator for sinusoidality) yielded a main effect only for 'group' and body part ($F = 13.04$; $p < 0.01$ and $F = 53.82$; $p < 0.001$, respectively), whereas 'emotion' was marginally significant ($F = 3.6$; $p = 0.052$). The three-way interaction emotions × body parts × group and the two-way interaction emotion × group were not significant. However, the interactions body part × group and emotion × body part were significant ($F = 10.02$; $p < 0.005$ and $F = 5.67$; $p < 0.005$, respectively). Figure 4 illustrates the differences between the naïve subjects and the actors. Similarly to our analysis of the amplitude energy, we examined each of the leg segments individually (Figure 5). Movements of the thigh showed a main effect only for 'emotion' ($F = 5.93$; $p < 0.05$); 'group' and the interaction emotion × group were not significant (Figure 5a). The ratios of the amplitudes of the first two harmonics of the shank showed main effect for both 'emotion' ($F = 5.53$; $p < 0.005$) and for the interaction emotion × group ($F = 6.03$; $p < 0.005$). The group factor was not significant (Figure 5b). The foot showed a main effect for both 'emotion'



(a) Thigh (b) Shank (c) Foot

Fig. 3: Average energy of the amplitude of the first harmonics for the naïve subjects and the actors for the various emotions.

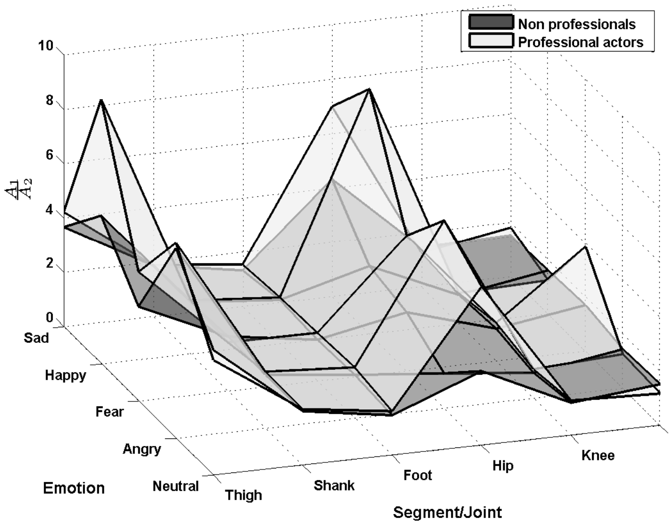


Fig. 4: Average ratios of the amplitude of the first to the second harmonic. Shown as in Figure 2.

and ’group’ ($F = 12.05$; $p < 0.0001$ and $F = 18.47$; $p < 0.0001$, respectively), but the interactions between these factors was not significant (Figure 5c).

Like the energy measure, the ratios of the first and second harmonics were consistently influenced by emotion. In contrast, the group factor and the different interactions cannot serve as stable classifiers.

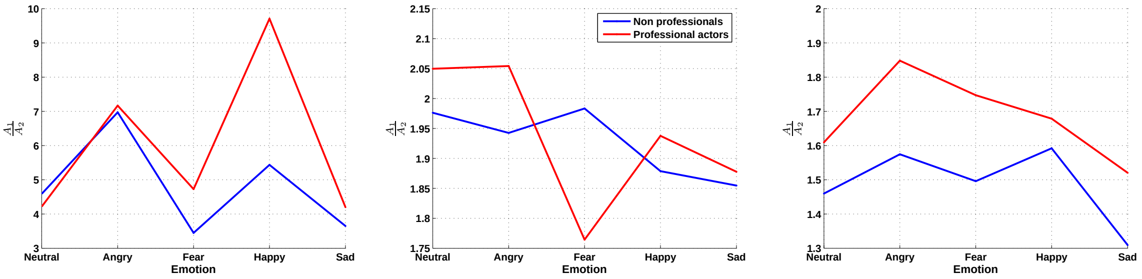
3.3 Intersegmental frequency ratio: $\frac{\omega_1}{\omega_2}, \frac{\omega_2}{\omega_3}, \frac{\omega_1}{\omega_3}$

The planarity of the intersegmental pattern of coordination is mainly determined by the fundamental frequencies of the different sinusoids (Barliya et al 2009) and planarity is observed when all frequencies are equal. Alternatively, if only two frequencies are equal, their corresponding phases should be equal. To analyze the frequency ratios between the different segments for the different emotions, body segments and subject groups, we performed a three-way ANOVA with subject group as a between-subject factor, and ’emotion’ and ratio type (ω_1/ω_2, ω_2/ω_3 or ω_1/ω_3) as within-subject factors. Here, none of the main effects or the possible interactions showed statistical significance. Investigating the ratios of each of the segments independently using two-way ANOVA on the data shown in Figure 6 produced the same result; no main effect was found for any of the factors or interactions.

3.4 Phase shifts between segments

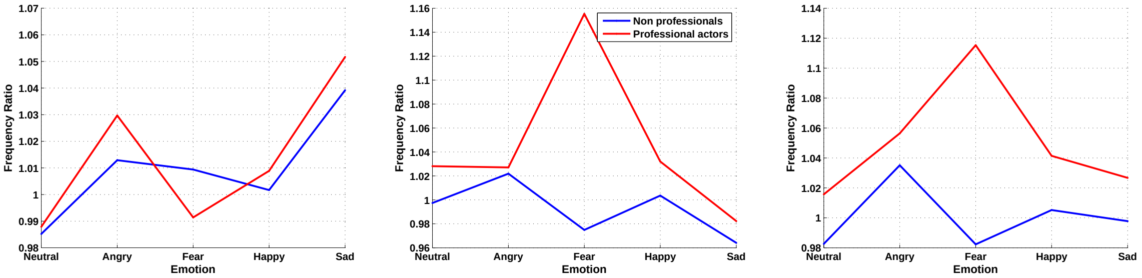
Phase shifts between the first harmonics of the various segments have been correlated with changes in gait velocity and energy expenditure. To analyze the phase shift parameters we performed a three-way ANOVA with subject group as a between-subject factor, and emotion and phase shift ($\varphi_1 - \varphi_2$, $\varphi_2 - \varphi_3$ or $\varphi_1 - \varphi_3$) as within-subject factors. Analyzing the phase shifts for both subject groups showed statistically significant main effects for emotion and phase shift ($F = 32.65$; $p < 0.0001$ and $F = 139.43$; $p < 0.0001$), but not for ’group’. The resemblance between the two groups can be easily seen in Figure 7. The three-way interaction emotion × phase type × group and the two-way interactions emotion × group and phase type × Group were not significant. However, the interaction emotion × phase type was significant ($F = 10.12; p < 0.0001$).

Once again we inspected each of the possible phase shifts independently (Figure 8). A two-way ANOVA revealed that ’emotion’ gave the only significant main effect for the thigh-shank phase shift (Figure 8a) ($F = 4.38$; $p < 0.005$) but the interaction emotion × group was not significant. As with phase shift between the shank and the foot (Figure 8b), significant main effects



(a) Thigh (b) Shank (c) Foot

Fig. 5: Average ratios of the amplitude of the first and second harmonics for the naïve subjects and actors for the different emotions.



(a) $\frac{\omega_1}{\omega_2}$ (b) $\frac{\omega_2}{\omega_3}$ (c) $\frac{\omega_1}{\omega_3}$

Fig. 6: Average ratios of the frequencies of the different segments for the different emotions. The frequencies of the thigh, shank and foot are represented by ω_1, ω_2 and ω_3, respectively.

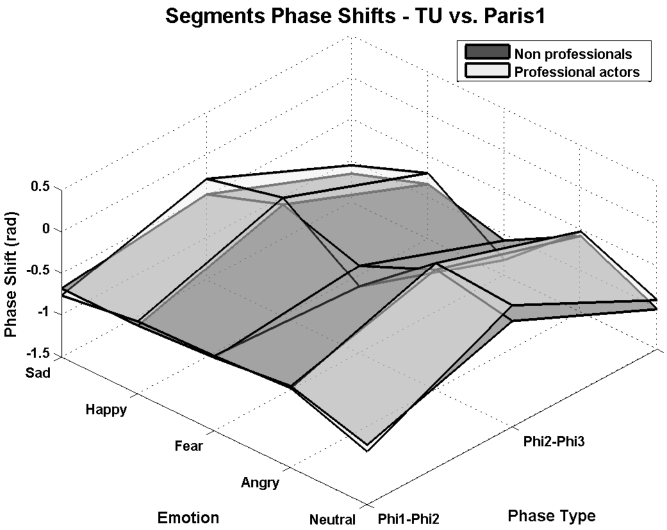
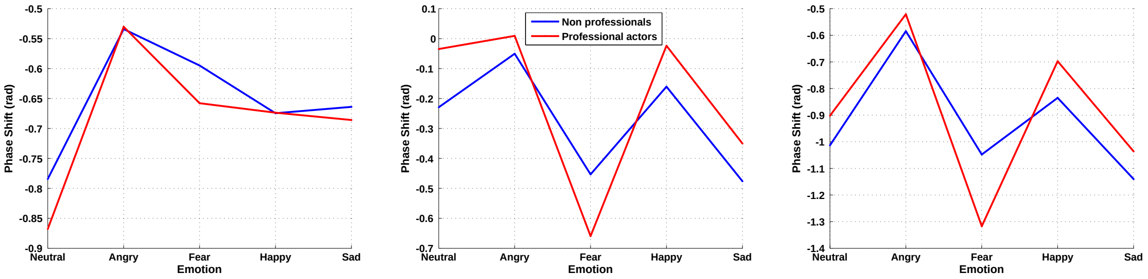


Fig. 7: Average phase shifts between the different segments of the leg for the various emotions: thigh-shank ($\varphi_1 - \varphi_2$), shank-foot ($\varphi_2 - \varphi_3$) and thigh-foot ($\varphi_1 - \varphi_3$).

were found for both 'emotion' ($F = 24.67$; $p < 0.0001$) and the interaction emotion×group ($F = 4$; $p < 0.05$). These phase shifts directly affected the orientation of the intersegmental plane (Barliya et al 2009). The phase shift between thigh and foot showed a main effect for 'emotion' ($F = 33.65$; $p < 0.0001$) (Figure 8c) and the interaction emotion × group was significant ($F = 3.89$; $p < 0.05$).

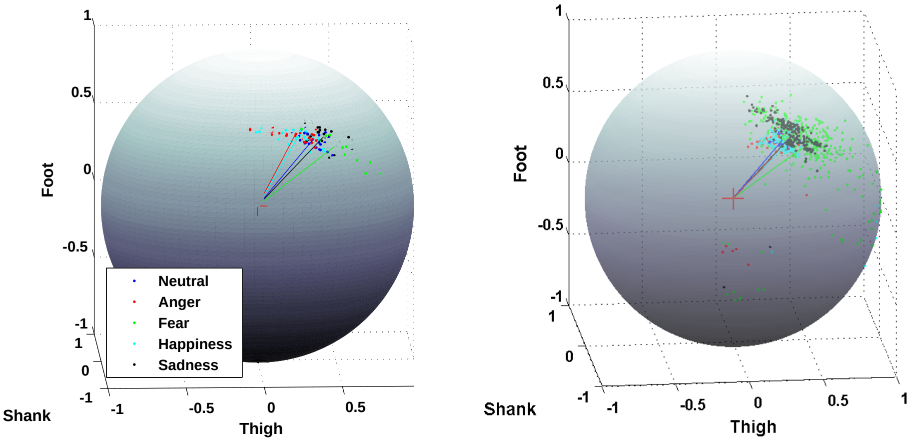
3.5 Plane orientation and Model Predictions

The measure of the orientation of the intersegmental plane has previously been associated with gait velocity and control of energy expenditure (Bianchi et al 1998). The plane rotates westward on the unit sphere with increasing gait speed. This rotation, reducing energy expenditure, to some extent compensates for the increased energy requirement due to increased speed. Figure 9 illustrates the projections of the unit normals onto the intersegmental plane on the unit sphere for both the naïve subjects and professional actors for the various emotions. For both subject groups the average orientations of the vectors for anger, joy, neutral, sad-



(a) $\varphi_1 - \varphi_2$ (b) $\varphi_2 - \varphi_3$ (c) $\varphi_1 - \varphi_3$

Fig. 8: Average phase shifts between the different segments for the various emotions. The phases of the thigh, shank and foot are represented by φ_1, φ_2 and φ_3, respectively.



(a) (b)

Fig. 9 Projections of the unit normals to the plane of intersegmental coordination on the unit sphere for the naïve subjects and actors. The solid vector lines indicate the average direction of the orientation of the plane for each emotion.

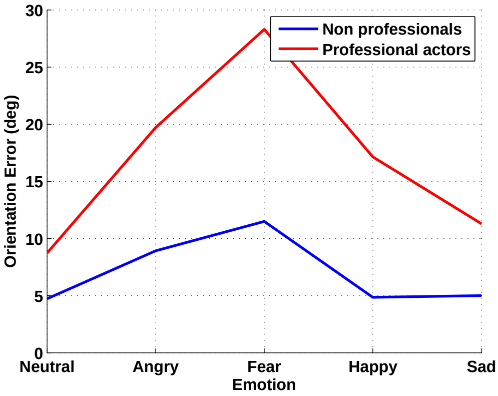


Fig. 10: The difference between the orientation of the intersegmental plane calculated from our data (using PCA) and that predicted using Equation 7. The difference is given in degrees.

ness and fear in Figure 9) were ordered on the sphere from "west" to "east". This order fitted the walking speed associated with these emotions, fastest for anger, slowest for fear.

Last, we compared how well the model in Barliya et al (2009) predicted the orientation (according to Equation. 7) for each of the emotions and groups with respect to the orientation computed using PCA (Figure 10). For the naïve group, the model predicts the orientation of the plane during the neutral condition and happiness and sadness rather well ($< 5^\circ$ error). On the other hand, the model was less accurate in predicting the orientation of the intersegmental plane for the professional actors. However, note that the same error pattern holds. That is, the error in prediction increases for both groups during the anger and fear conditions. The model's ability to predict the orientation decreased when the elevation angles of the leg became less sinusoidal, or when the fundamental frequencies of the leg segments were not equal ($\omega_1 \neq \omega_2 \neq \omega_3$). Figure 6 shows that, for the professional group, the ratios between the different frequencies were generally farther from 1 than those of the naive subjects (and thus the frequencies were not equal), although, both groups showed no statistically significant differences with respect to frequency ratios. It can be shown, however, that the planarity is very sensitive to changes in these ratios (see supplementary material of Barliya et al (2009))

3.6 Effects of speed

So far we have compared the kinematic parameters among emotions and between the two subject groups. However, emotions affect gait speed (Gross et al 2007; Roether et al 2009; Hicheur et al Unpublished), with anger and happiness generally accompanied by higher gait speed than sadness and fear. Figure 11 illustrates the significant change in locomotion speed found here for the various emotions ($F = 183.59; p < 0.0001$). The gait speeds associated with the different emotions were all found to be significantly different ($p < 0.0001$) except for the difference between neutral and happy. As locomotion speed increases, the swing phase becomes longer relative to the stance phase (Hreljac 1995). Figure 12 shows that the changes in speed during the different emotions consistently affected the timing of the transition between the swing and stance phases, consistent with expected changes due to gait speed. Swing phases occupy on average 38% of a gait cycle and stance phases occupy 62% in normal healthy young men (Vaughan et al 1999). Here, during sadness and fear, the swing phase occupied 33% and 34% of the gait cycle, respectively. Anger showed the fastest gait and accordingly a larger portion of the gait cycle was devoted to the swing phase (38%).

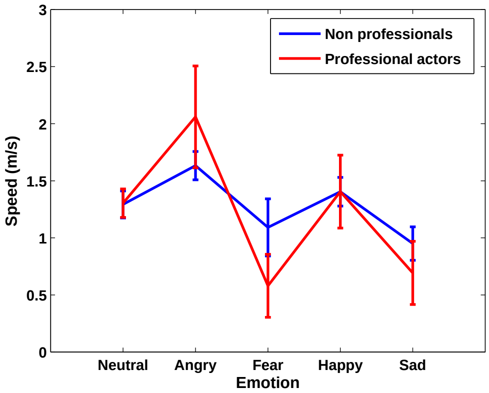


Fig. 11: Average locomotion speed for each emotion in the two groups. Bars represent standard deviation.

Since kinematic parameters are influenced by speed, we now checked whether the observed changes were due only to speed or whether each emotion produced other effects on locomotion. Roether et al (2009) have recently addressed a similar question. For each actor they compared emotional with neutral gaits whose speeds were matched to those of the emotional gaits on a trial-by-trial basis. While gait speed alone induces changes in perceived emotions (e.g. Roether et al (2009)), Hicheur et al (Unpublished), using artificially generated emotional gaits, found that manipulating speed alone is not sufficient to reach significant rates of emotion recognition. To address this question we applied a linear regression analysis to each of the parameters using speed as the predictor and compared the slopes of the regression lines (see *methods* for details). The slope indicates the rate of change of a parameter with speed. A difference in slope of a parameter during emotion and the neutral condition indicates an emotional effect beyond that expected from speed alone.

Figures 13-15 show the changes with respect to speed for both groups. The slopes of the regression lines for each emotion were compared to the neutral condition for each group and between groups. Figure 13 shows the amplitudes of the elevation angles of the leg segments as a function of speed. Both groups showed similar differences for the various emotions. For example, the amplitude of the thigh elevation angle for all emotions except sadness increased with speed in a manner indicating the effect of factors other than speed. The groups showed a notable difference in the amplitude of thigh elevation angle during happiness or sadness. They also differed in amplitudes of foot elevation angle during the neural locomotion, sadness and fear.

The phase shift between the shank and foot (Figure 14), which is strongly related to the rotation of the plane with speed, showed no significant difference for the various emotions and between groups. Only happiness showed a difference between naïve subjects and actors. The remaining phase shift quantities ($\varphi_1 - \varphi_2$ and $\varphi_1 - \varphi_3$) showed no fundamental differences.

To examine how the orientation of the plane changed with speed for different emotions, the elements of the normals to the plane were linearly regressed with gait speed. Recall that the elements of the normal according to the model (7) are functions of the segments' amplitudes and the phase shifts between them. For brevity, let the elements of the normal be denoted by n_1, n_2 and n_3, designating the plane orientation with respect to the thigh, shank and foot semi-axes, respectively. Here, rotation of the plane roughly about the long axis of the loop of covariation pattern on the plane (n_1) showed significant differences only between anger and fear and anger and sadness in both groups. The orientation of the plane with respect to the shank semi-axis (n_2) dif-

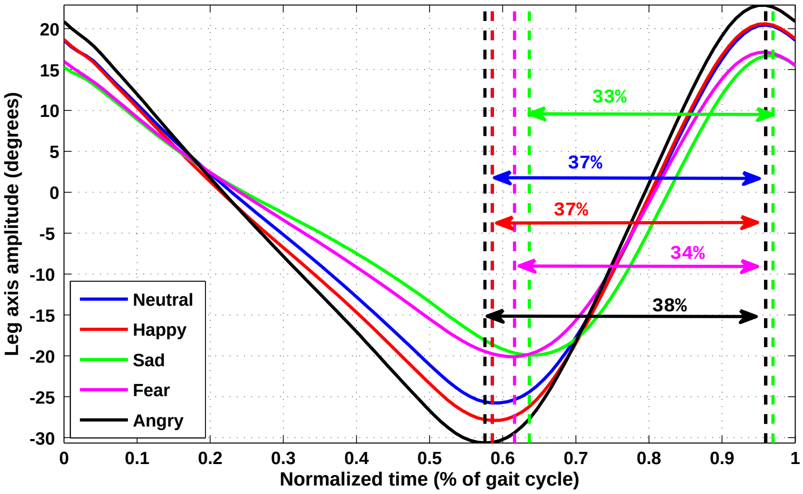


Fig. 12 Average leg-axis elevation angle. The leg-axis is the line connecting the hip and the ankle. The minimum and maximum values of the leg-axis elevation angles are good approximations of the toe-off and heel-contact phases, respectively, that bound the swing phase (Bianchi et al 1998). The vertical dashed lines indicate the times of the minimum and maximum elevation angles. The average swing phase percentages of the gait cycle are indicated for each emotion by the double-sided arrows.

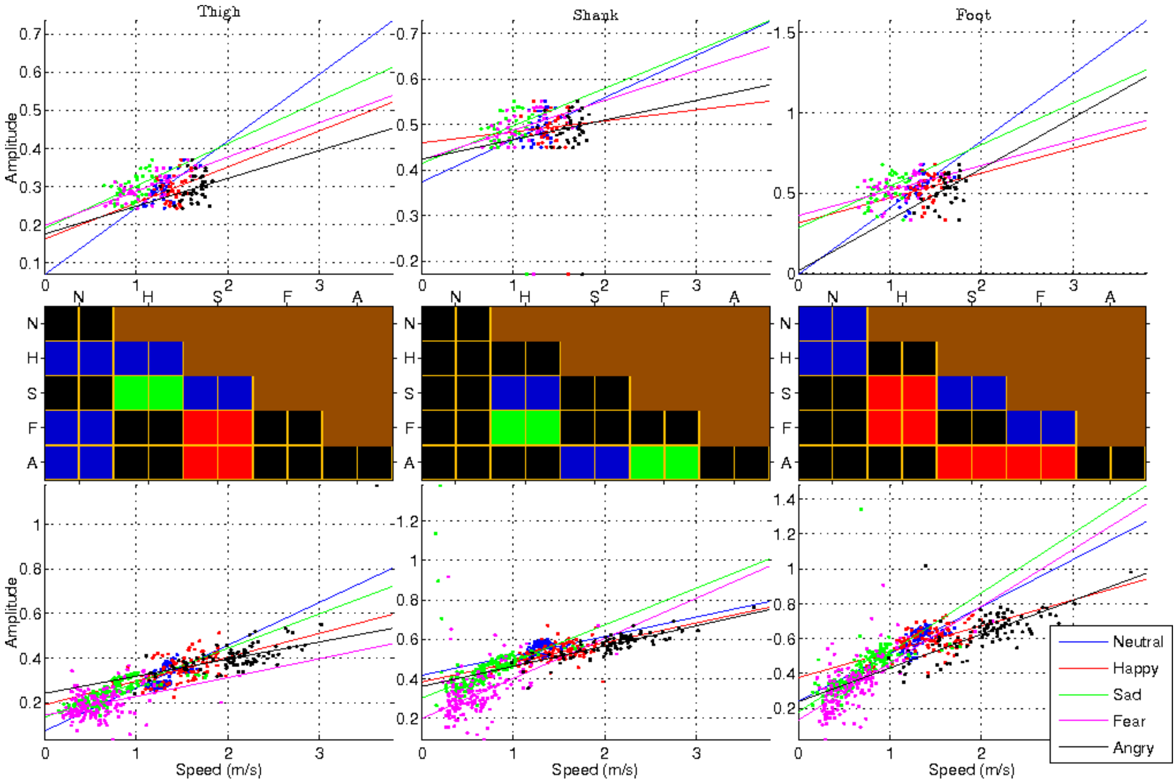


Fig. 13: Comparison of the change in the amplitudes of elevation angles of thigh, shank and foot with speed. First row, naive subjects; third row, professional actors. Each dot represents a gait cycle and the lines result from a robust regression procedure (accounting for possible outliers). The grids in the middle row present the results of the statistical t-tests for comparing the slopes. In each grid N, H, S, F and A stand for neutral, happiness, sadness, fear and anger, respectively. For each emotion the left column represents the naive subjects, the right the professional actors, with the columns showing within-group comparisons for each emotion. Cells on the grids' diagonals relate to comparison between groups for that emotion. Black cells designate no significant difference. Blue, green and red cells denote a statistical difference with p values of less than 0.05, 0.005 and 0.0005, respectively.

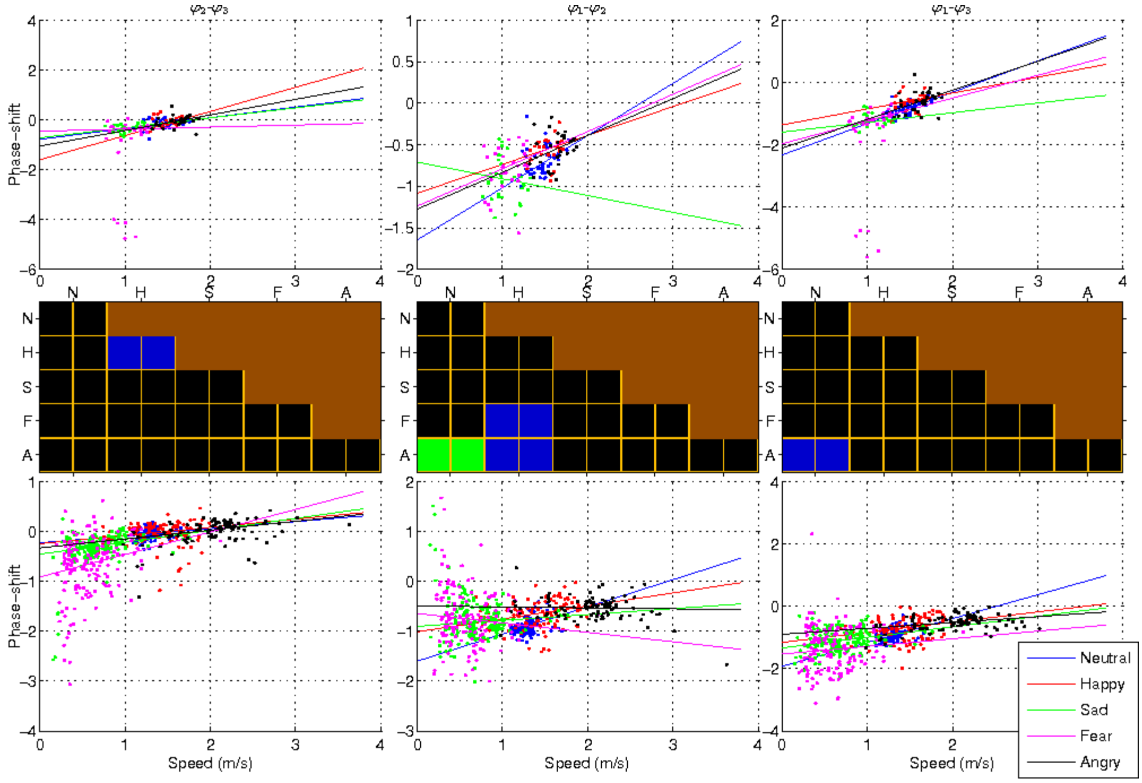


Fig. 14: Comparison of the slopes of the regression lines for the phase shifts ($\varphi_2 - \varphi_3$,$\varphi_1 - \varphi_2$ and $\varphi_1 - \varphi_3$) as in Figure 13.

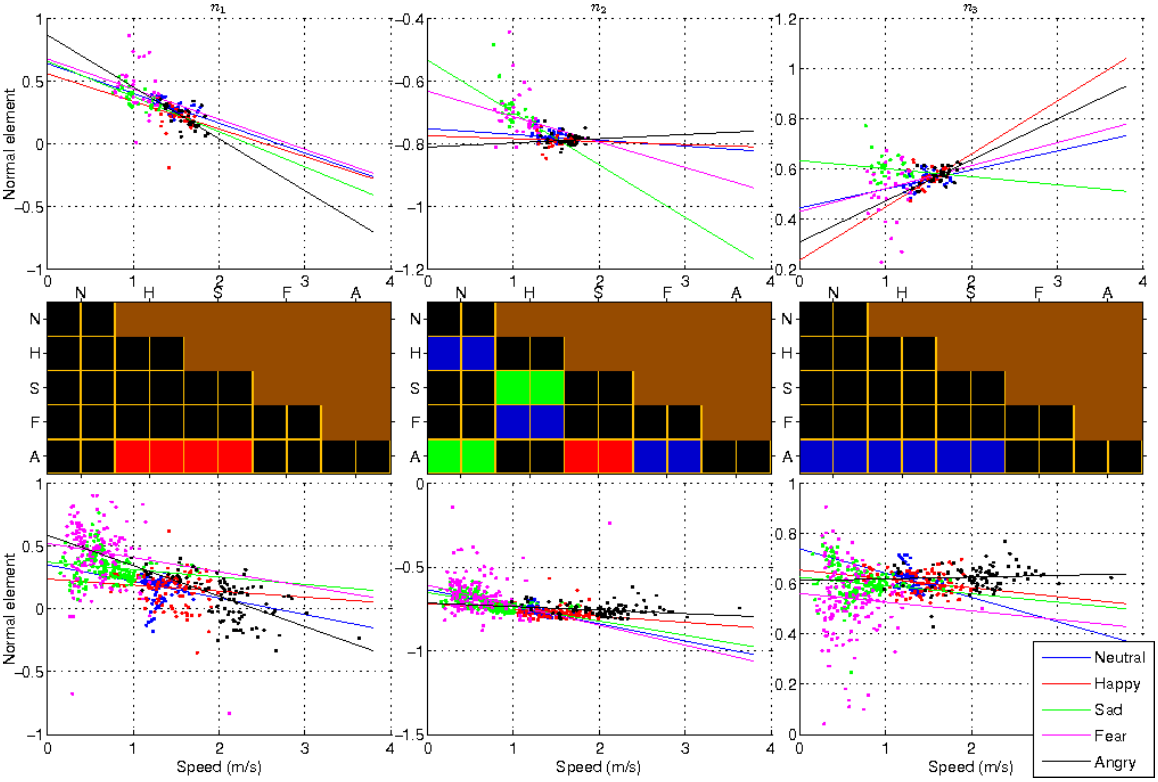


Fig. 15: Orientation of the plane of intersegmental coordination about the 3 possible axes of rotation with respected to gait speed. As in Figure 13.

fered significantly for anger compared to all emotions except happiness. The third element of the normal to the plane (n_3) also differed significantly for anger compared to the other emotions except fear. Thus, anger was the only emotion consistently showing differences from other emotions in how the orientation of the plane changed with speed.

4 Discussion

We have investigated the effect of basic human emotions (anger, fear, happiness and sadness) on locomotion, comparing locomotion expressing the different emotions with locomotion during a neutral emotional state. Using naïve subjects (university students) and professional actors we analysed the kinematic properties of leg movements in the context of the law of intersegmental coordination. We therefore used differences in amplitude, frequency and phase of the relevant harmonics to compare locomotion expressing the various emotions. We discuss here the main findings pertaining to the influence different emotions have on the kinematic characteristics of leg movements beyond the effect of speed. We examine how our observations fit with current emotion theories and conclude with a discussion of these findings from a neural control perspective.

4.1 The law of intersegmental coordination

We investigated how the parameters affecting the planarity and orientation of the plane of intersegmental coordination during human locomotion are affected by the emotional state of the subjects and whether these changes are only due to the change in speed associated with different emotions or not. The previous research on the effects of emotion on the locomotion kinematic parameters not due to speed (Roether et al 2009) differs from the current study in two respects:

1. The main focus in Roether et al (2009) was on the upper-body and upper limbs.
2. The movements of anatomical joint angles and separate limb segments were analyzed but the study did not focus on intersegmental coordination.

Here, we concentrated on the lower body and investigated the elevation angles of the legs as part of a motor control principle, i.e., the law of intersegmental coordination. We were not interested in the elevation angles themselves but in the coordination between the different segments which is reflected in the orientation of the emergent plane (Borghese et al 1996). Increasing gait speed causes a monotonic change in the orientation of the planar covariation that leads to reduction of the energy expenditure that would otherwise occur. The importance of the orientation of the plane lies in its correlation with energy expenditure and because the control of coordination may reflect a compensatory mechanism reducing energy cost with increasing speed (Bianchi et al 1998; Lacquaniti et al 1999). This change in orientation is mainly effected by the change in phase-shift between the shank and foot elevation angles. Barliya et al (2009) have proposed a model that accurately describes the orientation of the plane and corroborates the above results on the phase shifts between the leg segments. Their model also identified conditions with respect to the frequencies of the elevation angles that need to be met for the plane to exist, and mathematically predicted the dependency of the orientation on the amplitudes of the angular rotations.
Speed affects each of these parameters. Thus we study them here as low level controlled parameters that, by affecting the orientation of the plane, may limit energy expenditure possibly even beyond or in contrast to the effect of speed on energy costs.

4.1.1 Amplitudes of Fourier harmonics

The "energy" in the first harmonic of each leg segment and the ratio between the amplitudes of the first and second harmonics were used as measures of sinusoidality. The higher these values, the more sinusoidal the pattern of angular behavior of the segments and the smoother the motion. Whenever higher harmonics are equal to or more dominant than the lower harmonics, the angular behavior becomes noisy and departs from a simple signal that can be represented with fewer harmonics. The "energy" of the first harmonic for the thigh, shank and foot segments followed the same pattern across emotions and subjects but the amount of energy differed in each emotion, especially for the foot. The ratios between the first two harmonics differed between the groups across emotions even though they followed the same pattern as the "energy" parameter. This ratio between the first two harmonics revealed that during locomotion expressing happiness the professional actors moved the thigh considerably more sinusoidally than the naïve subjects. During fear the professional actors seemed to rotate the shank more sinusoidally. Overall, the professional group rotate their leg segments more smoothly and sinusoidally than the naïve group.

The model we use to predict the intersegmental plane of coordination (Barliya et al 2009) relies on the sinusoidality pattern of each of the leg segments during locomotion. Below we examine how these patterns affected the success of the model in predicting the intersegmental plane.

4.1.2 Harmonic phases and energy expenditure

The phase shift between the shank and foot ($\varphi_2 - \varphi_3$) decreases monotonically with increase in gait speed during emotionally neutral locomotion (Bianchi et al 1998). Both experimentally (Bianchi et al 1998) and mathematically (Barliya et al 2009) this phase shift has been found to be significant in determining the orientation of the intersegmental plane. The orientation of this place is important as the CNS is thought to use the orientation to limit energy expenditure (Bianchi et al 1998; Lacquaniti et al 1999). Here we found a main effect only for the emotion factor, which was also significant for the remaining phase relations. There was no effect for the group factor. This is interesting as Amaya et al (1996) have suggested that subtle phase relations may carry information about affect. We discuss this below. Using the approach suggested in Omlor and Giese (2007), Roether et al (2009, 2010) confirmed that emotions affect movement speed (Crane and Gross 2007) by extracting the primitives.

They showed how the weights (amplitudes) of the sources for each joint become larger for anger and happiness and smaller for sadness and fear. Here we normalized all gait cycle durations to $T = 1$. As this normalization did not cancel the effect of speed on the phase shifts, we needed to determine whether the differences in phase shifts resulted only from changes in locomotion speed associated with different emotions, or whether there is another mechanism affecting the phase shifts irrespective of gait speed. That is, can the emotional state directly influence the motor system, not only through the direct effect on speed? We address this question below.

4.1.3 Plane orientation

Both subject groups showed a similar progression of the orientation of the plane from "west" to "east" for the emotions in the following order: anger, happiness, neutral, sadness and fear. Gaits associated with a planar covariation rotated more westward (faster) are more expensive in terms of energy than gaits with planes rotated eastward (slower) (Bianchi et al 1998). Our data are consistent with this principle both intuitively, anger and happiness being more "energetic" than sadness and fear, and also in relation to speed, as angry and happy people tend to move faster than sad and frightened ones (Crane and Gross 2007).

4.2 Beyond the effect of speed

As discussed above, different emotions are generally associated with different movement and locomotion speeds. Speed affects locomotion parameters such as amplitudes of elevation angles and phase shifts between leg segments (Bianchi et al 1998). Arm swing amplitude increases with walking speed (Donker et al 2001, 2002; Hicheur et al Unpublished) and the stance phase knee flexion increases (Kirtley 2006). To differentiate the emotions expressed by walkers, Montepare et al (1987) examined gait characteristics such as arm swing, stride length, heavy footedness, and walking speed. We focused on the effect of speed both as the major discriminator among emotions and its direct effect on the other parameters such as stride length. Speed plays a significant role in the recognition of emotion, but Paterson et al (2001) showed that when the speed of angry movements was artificially adjusted, participants still tended to classify them as angry. They rated the faster gaits as more intense and the slower ones as less intense. Similarly, Roether et al (2009) also found an influence of speed on differentiation of emotional perception from neutral gaits. Atkinson et al (2004) proposed that speed or vigor can enhance perceived emotional intensity. Thus, it appears that speed intensifies the perceived emotion if it changes in the direction of the natural[1] speed of the conveyed emotion, with higher speeds intensifying anger and slower speed enhancing sadness.

Since speed can facilitate changes in emotion intensity but not content, there must be more to the kinematics of emotion than speed. Roether et al (2009) provided valuable insights by comparing emotional gaits with neutral gaits of matched speed. They obtained similar results to our comparison with neutral gaits not matched for speed. That is, weights (amplitudes) of the sources (Omlor and Giese 2007) extracted for the joint angles increased for the activating emotions anger and happiness, especially for the shoulder and elbow joints and decreased during sadness and fear. Furthermore, for the matched speed comparison, all emotions showed significant differences, thus confirming the existence of emotion-specific kinematic features independent of changes in gait speed.

Here we attempted to identify parameters encapsulating information about the expressed emotion other than speed. Comparing all emotions to the neutral condition, for all emotions except sadness the thigh amplitude changed differently from what could have been expected from speed alone. In contrast, phase shifts showed almost no differences among emotions or groups.

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[1] Fear, sadness - low speeds. Joy, anger - high speeds.

Recall that the orientation of the intersegmental plane is determined by some coupling of the amplitudes and phases of the elevation angles (Barliya et al 2009). While amplitudes and phases alone are not entirely informative, the orientation of the plane, correlated with the reduction of energy expenditure for higher gait speeds (Bianchi et al 1998), behaved differently during emotional walking, especially during anger. The change in the orientation of the plane with speed during angry gait differed significantly from that with other emotions. This finding may explain the observations of Paterson et al (2001), Dittrich et al (1996), and Walk and Homan (1984) on perception of emotions in dancing in which anger was the most reliably identified emotion. Thus, angry movements may contain more information encoded in the kinematics beyond the effect of speed. Finally, our finding also partially agrees with Walk and Homan (1984)'s "alarm hypothesis" according to which expressions of anger and fear are more readily recognized than other emotions.

4.3 The Emotion Perspective

4.3.1 Residual Effects of Emotion

So far we have focused on kinematic changes observed during locomotion during different emotional states. Our analysis was able to cancel out the effect of speed on kinematics and focus on the residual effects of emotion on gait patterns. Both the professional and naïve subjects behaved similarly in terms of high level strategy (e.g., orientation of the intersegmental plane). That is, despite the large variability in the ability of actors to encode emotion, and given that this variability becomes even more prominent when comparing professional and naïve subjects, there is a stable phenomenon with respect to the effect of speed. This was also found by Wallbott (1998).

Differences observed between professional actors and naïve subjects at the overall level of motion (e.g., smoothness) were also reflected in how well the orientation of the plane could be predicted by the model. The model developed by Barliya et al (2009) did not perform as well for the professional as for the naïve subjectsm, possibly due to exaggeration during performance. However, the more actors exaggerate their portrayals of emotion, the more accurate people are at identifying the emotion (Atkinson et al 2004; Pollick et al 2003, 2001a; Hill and Pollick 2000). Clearly, a major part of the training of professional actors is to accurately convey their own emotion. They may achieve this through exaggeration, even if subtle.

Emotions, as we know them, developed in mammals, well after the evolution of the bodies adapted to interaction with the external environment and generating locomotory movements. This could explain why, in spite of their functional significance, emotions often only finetune the characteristics of these more fundamental actions (Amaya et al 1996). The model of Barliya et al (2009) provides only a first order approximation for the law of intersemental coordination. Information residing in higher harmonics not captured by the model must be taken into account to provide a more complete description of the effect of emotions on kinematics and intersegmental coordination.

4.3.2 Theories of Emotion

Sadness and fear are associated with avoidance and withdrawal behaviors, while happiness and anger are considered to be associated with approach. The differences between the emotions associated with approach versus withdrawal behaviors are manifested in the gait kinematic features even after removing the effect of speed, e.g., the amplitudes of the shank and foot movements differ significantly. Likewise, the thigh amplitude differed when comparing anger and happiness with sadness. The orientation of the intersegmental plane similarly allowed distinction between these emotional groups but only with respect to a rotation about an axis which does not reduce energy expenditure when gait speed increases. Possibly, when removing the effect of speed, the remaining rotation of the intersegmental plane reflects kinematic changes which serve to express the different emotions. This requires further investigation.

Alternatively, the results can be analysed in the context of discrete versus dimensional theories of emotion. In the *discrete model* each emotion is thought to emerge from an independent neural system (Scherer 2000). This model cannot capture our large variety of distinct emotional experiences. In the *dimensional model* all affective states arise from two fundamental neurophysiological systems, one related to valence (a pleasure-displeasure continuum) and the other to arousal, or alertness (Russell 1980). Thus, each emotion can be understood as a linear combination of these two dimensions, the circumplex model (Posner et al 2005).

Our experimental design assumes a discrete emotional representation as the subjects were asked to recall an event for each of the basic emotions. However, our results may not support a clear distinction between the kinematic parameters associated with the different emotions, as already implied by our dividing the emotions with respect to positive and negative valences.

In the circumplex model sadness comprises low valence and low arousal, happiness is characterized by high valence and mild arousal, anger and fear are both related to a high arousal, however fear is distinguished by a lower valence (both negative). While our results cannot confirm or refute the above division, the lack of strong distinction between the emotions when the effect of speed is canceled out (Figures 13-15) and a gradual transition between related emotions may indicate complex influence of and interactions among several neuronal networks. This would fit Russell and Fehr (1994) claim that emotions seem to lack discrete borders clearly differentiating one emotion from another. Also, studies of subjective experience of emotion have noted that emotions are intercorrelated (Russell and Carroll 1999).

4.4 Neural Substrates & Central Pattern Generators

The neural networks driving repetitive movements motions are often called central pattern generators (CPGs). These circuits may not be located in the brain but in the spinal cord (Grillner 1996) The lumbar spinal cord contains sufficient neuronal elements to produce the precise timing and activation of the large number of hindlimb muscles used during locomotion (Grillner 1981). A fully functioning CPG should support three main features to facilitate locomotion (Kiehn 2006):

1. Setting the rhythm
2. Ipsilateral coordination of flexor/extensor across the same or different joints within a limb
3. Left/right coordination

As the amplitude of locomotor output can change independently of a change in locomotor speed, i.e., the pattern can be changed independently of the rhythm (Kriellaars et al 1994), mammalian locomotor CPGs-may have two layers: a rhythm-generating layer and a pattern-generating layer (for coordination of flexor-extensor and left-right activity) (Burke et al 2001; Degtyarenko and McCrea 2005). If this is the case, then circuits relaying emotional affect could directly influence the pattern of locomotion independently of speed. Grillner (1996) has suggested the following scheme for human locomotion:

> ”Specialized neural circuits in the forebrain select among an array of ”motor programs” by activating specific parts of the brain stem. The brain stem in turn initiates locomotion and controls the speed of these movements by exciting neural networks (called central pattern generators) located within the spinal cord. These local networks contain the necessary control circuitry to start and stop the muscular contractions involved in locomotion at the appropriate times.”

Thus, an emotion-related circuit must intervene before the motor program is selected and activated by the brain stem. Such intervention is indeed possible via basal ganglia and brainstem loops that may be involved in the appropriate expression of locomotor behaviors by integrating volitional and emotional signals from the forebrain (Takakusaki et al 2004). Finally, emotional aspects of motor behavior are possibly affected by projections from the limbic structures (hippocampus and amygdala) to the nucleus accumbens (Grillner et al 1997).

To conclude, many emotion studies have investigated how kinematic parameters of locomotion are affected during different emotional experiences. They all report that speed, is one of the most prominent variables changing with different emotions. This may explain some of the differences in the gait patterns observed in most of these studies. Only few attempts have been made to tackle the role of speed in determining changes in gait patterns under different emotional conditions (see Roether et al (2009)). Here, we show quantitatively the effect of speed on the kinematic variables associated with intersegmental coordination during human locomotion during emotional and neutral conditions. Further studies are required to discover the system responsible for the motor manifestations that are not a direct outcome of changes in speed.

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References

Amaya K, Bruderlin A, Calvert T (1996) Emotion from motion. In: Graphics Interface 96, pp 222–229

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

Barliya A, Omlor L, Giese MA, Flash T (2009) An analytical formulation to the law of intersegmental coordination. Experimental Brain Research 193(3):371–385

Bianchi L, Angelini D, Orani G, Lacquaniti F (1998) Kinematic coordination in human gait: Relation to mechanical energy cost. J Neurophysiol 79:2155–2170

Borghese N, Bianchi L, Lacquaniti F (1996) Kinematic determinants of human locomotion. Journal of Physiology 494(3):863–879

Bruderlin A, Williams L (1995) Motion signal processing. In: SIGGRAPH'95, pp 97–104

Burke RE, Degtyarenko AM, Simon ES (2001) Patterns of locomotor drive to motoneurons and last-order interneurons: clues to the structure of the cpg. Journal of Neurophysiology 86:447–462

Cheron G, Bouillot E, Dan B, Bengoetxea A, Draye JP, Lacquaniti F (2001) Development of a kinetic coordination pattern in toddler locomotion: planar covariation. Experimental Brain Research 137:455–466

Cluss M (2006) Effect of emotion on the kinematics of gait. American Society of Biomechanics

Courtine G, Schiepati M (2004) Tuning of basic coordination pattern constructs straight-ahead and curved walking in humans. Journal of Neurophysiology 91:1524–1535

Crane E, Gross M (2007) Motion capture and emotion: Affect detection in whole body movement. In: Affective Computing and Intelligent Interaction, vol 4738/2007, Springer Berlin / Heidelberg, pp 95–101

Degtyarenko M, McCrea DA (2005) Deletions of rhythmic motoneurons activity during fictive locomotion and scratch provide clues to the organization of the mammalian central pattern generator. Journal of Neurophysiology 94:1120–1132

Descrates R (1649) Les Passions de l'âme. A series for the classics of Philosophy, Resling Publishing, 2007, hebrew translation. Translated from French by Ido Bassok

Dittrich WH, Troscianko T, Lea S, Morgan D (1996) Perception of emotion from dynamic point-light displays represented in dance. Perception 25(6):727–738

Donker SF, Beek PJ, Wagenaar RC, Mulder T (2001) Coordination between arm and leg movements during locomotion. Journal of Motor Behavior 33(1):86–102

Donker SF, Mulder T, Nienhuis B, Duysens J (2002) Adaptations in arm movements for added mass to wrist or ankle during walking. Experimental Brain Research 146(1):26–31

Fisher RA (1921) On the probable error of a coefficient of correlation deduced from a small sample. Metron 1:3–32

Giese MA, Poggio T (2000) Morphable models for the analysis and synthesis of complex motion patterns. International Journal of Computer Vision 38(1):59–73

Grillner S (1981) Handbook of Physiology: The Nervous System, 2, Motor Control, Bethesda, MA: American Physiology Society, chap Control of locomotion in bipeds, tetrapods, and sh, pp 1176–1263

Grillner S (1996) Neural networks for vertebrate locomotion. Scientific American pp 64–69

Grillner S, Georgopoulos AP, Jordan LM (1997) Selection and initiation of motor behavior. MIT Press, Boston

Gross M, Crane E, Fredrickson B (2007) Effect of felt and recognized emotions on gait kinematics. In: American society of Biomechanics Conference, Palo Alto, CA, ASB

Gross MM, Crane EA, Fredrickson BL (2011) Effort-shape and kinematic assessment of bodily expression of emotion during gait. Human Movement Science DOI 10.1016/j.humov.2011.05.001

Hicheur H, Kadone H, Grèzes J, Berthoz A (Unpublished) The combined role of motion-related cues and upper body posture for both the expression and the perception of emotions during human walking

Hill H, Pollick FE (2000) Exaggerating temporal differences enhances recognition of individuals from point-light displays. Psychological Science 11:223–228

Hreljac A (1995) Determinants of the gait transition speed during human locomotion: Kinematic factors. Journal of Biomechanics 28(6):669–677

Ivanenko Y, Grasso R, Macellari V, Lacquaniti F (2002) Control of foot trajectory in human locomotion: Role of ground contact forces in simultaed reduced gravity. Journal of Neurophysiology 87:3070–3089

Ivanenko YP, Cappelini G, Dominici N, Poppele RE, Lacquaniti F (2005a) Coordination of locomotion with voluntary movements in humans. Journal of Neuroscience 25(31):7238–7253

Ivanenko YP, Dominici N, Cappellini G, Lacquaniti F (2005b) Kinematics in newly walking toddlers does not depend upon postural stability. Journal of Neurophysiology 94:754–763

Ivanenko YP, d'Avella A, Poppele RE, Lacquaniti F (2008) On the origin of planar covariation of elevation angles during human locomotion. Journal of Neurophysiology 99(4):1890–1898

Kiehn O (2006) Locomotor circuits in the mammalian spinal cord. Annual Review of Neuroscience 29:279–306

Kirtley C (2006) Clinical Gait Analysis: Theory and Practice, Churchill Livingstone, chap 3, p 60

Kriellaars DJ, Brownstone RM, Noga BR, Jordan LM (1994) Mechanical entrainment of fictive locomotion in the decerebrate cat. Journal of Neurophysiology 71:2074–2086

Lacquaniti F, Grasso R, Zago M (1999) Motor patterns in walking. News Physiol Sci 14:168–174

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

Montepare JM, Goldstein SB, Clausen A (1987) The identification of emotions from gain information. Journal of Nonverbal Behavior 11(1):33–42

Naugle KM, Joyner J, Hass CJ, Janelle CM (2010) Emotional influences on locomotor behavior. Journal of Biomechanics 43:3099–3103

Omlor L, Giese MA (2007) Extraction of spatio-temporal primitives of emotional body expressions. Neurocomputing 70(10-12):1938–1942

Paterson HM, Pollick FE, Sanford AJ (2001) The role of velocity in affect discrimination. In: Proceedings of the 23rd Annual Conference of the Cognitive Science Society Edinburgh, pp 756–761

Pollick FE, Fidopiastis C, Braden V (2001a) Recognising the style of spatially exaggerated tennis serves. Perception 30:323–338

Pollick FE, Paterson HM, Bruderlin A, Sanford AJ (2001b) Perceiving affect from arm movement. Cognition 82:B51–B56

Pollick FE, Hill H, Calder A (2003) Recognising facial expression from spatially and temporally modified movements. Perception 32:813–826

Posner J, Russel JA, Peterson B (2005) The circumplex model of affect: an integrative approach to affective neuroscience, cognitive development, and psychopathology. Development and psychopathology 17(3):715–734

Roether CL, Omlor L, Christensen A, Giese MA (2009) Critical features for the perception of emotion from gait. Journal of Vision 9(6)(15):1–32

Roether CL, Omlor L, Giese MA (2010) Features in the recognition of emotions from dynamic bodily expression. In: Ilg UJ, Masson GS (eds) Dynamics of Visual Motion Processing, Springer US, pp 313–340

Russell JA (1980) A circumplex model of affect. Journal of Personality and Social Psychology 39:1161–1178

Russell JA, Carroll JM (1999) On the bipolarity of positive and negative affect. Psychology Bulletin 125:3–30

Russell JA, Fehr B (1994) Fuzzy concepts in a fuzzy hierarchy: Varieties of anger. Journal of Personality and Social Psychology 67:186–205

Sawada M, Suda K, Ishii M (2003) Expression of emotions in dance: Relation between arm movement characteristics and emotion. Perceptual and motor skills 97(1 pt.3):697–708

Scherer KR (2000) Psychological Models of Emotion, Oxford University Press, chap 6, pp 137–162

Takakusaki K, Saitoh K, Harad H, Kashiwayanagi M (2004) Role of basal ganglia-brainstem pathways in the control of motor behaviors. Neuroscience Research 50:137–151

Troje NF (2002) Decomposing biological motion: A framework for analysis and synthesis of human gait patterns. Journal of Vision 2:371–387

Unuma M, Anjyo K, Takeuchi R (1995) Fourier principles for emotion-based human figure animation. In: Proceedings of the 22nd annual conference on Computer graphics and interactive techniques, ACM, SIGGRAPH '95, pp 91–96

Vaughan CL, Davis BL, O'Connor JC (1999) Dynamics of Human Gait, 2nd edn. Kiboho Publishers

Walk R, Homan C (1984) Emotion and dance in dynamic light displays. Bulletin of the Psychonomic Society 22(5):437–440

Wallbott HG (1998) Bodily expression of emotion. European Journal of Social Psychology 28(6):879–896

Westermann R, Spies K, Stahl G, Hesse FW (1996) Relative effectiveness and validity of mood induction procedures: a meta-analysis. European Journal of Social Psychology 26:557–580

Yacoob Y, Black MJ (1999) Parameterized modelling and recognition of activities. Computer Vision and Image Understanding 73(2):232–247