

Short communication

# A novel method for displaying gait and clinical movement analysis data

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## Abstract

Plotting kinematic and kinetic data of a patient's movement patterns relative to normative values (i.e., mean and  $\pm 1$  S.D.) is a common method used by clinicians to visually assess deviations and interpret the patient's gait analysis data. This method of data interpretation is often time consuming and complex, especially when the process requires the inspection of a plethora of line graphs for numerous variables that are displayed across several report pages. In this paper we propose an alternate method for displaying movement pattern deviations relative to normative data by color-coding the magnitude and the direction of the deviation. An advantage of this approach is that a single page summary of all the deviation magnitudes can be displayed simultaneously, in a manner that is concise, visually effective and reduces complexity. The purpose of this paper is to describe the algorithmic development of the color-coding method.

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## 1. Introduction

Data visualization is used in all facets of business, the media and in academics. For example, meteorological data are often reported relative to historical values to display trends in weather patterns. Data visualization methods are widely used in commodity trading to exhibit the past, present and the future earning potential of a stock. In the study of human motion, kinematic and kinetic data are plotted to characterize the functional demands of the movement over time. In this paper, we propose a novel method of data visualization. The method is described in the context of clinical gait analysis. However, we wish to point out that it is not limited to this class of movements, or to human movement in general.

Human movement is inherently variable [1]. That is, although well-learned tasks are repeated in a manner that is similar from trial to trial, they are not performed exactly the same way every time [2]. Moreover, different people perform exactly the same task slightly differently [3]. Intra and

inter-subject variability are natural elements of movement patterns associated with functional tasks.

Normal movement implies that the time-history of the pattern lies within a range of values that are distributed about a time-varying mean. For example, when data for a group of subjects are re-sampled to 100% of the stance phase of gait and averaged at discrete intervals, there is a mean and standard deviation (S.D.) that characterizes the group at every interval "i" in the normalized cycle. The greater the standard deviation at "i", the greater the inter-subject variability at that interval. Plotting an individual subject's data along with normative values (i.e., mean and  $\pm 1$  S.D.) is a common method of visually assessing normality [4].

It is not uncommon for a clinical gait report to contain upwards of 50 line graphs when bi-lateral data for the ankle, knee and hip are presented. Synthesis and interpretation of this expansive amount of data can present a challenge to even the most experienced clinician. Part of the difficulty can be attributed to the spatial vertical dimension of the line graphs. The vertical axes must be of sufficient height so that subtle changes in the dependent variables can be detected visually and, therefore, clinical gait reports necessarily span multiple pages.

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We propose an alternate method of reporting movement pattern deviations relative to normative data by color-coding the magnitude and the direction of the difference. An advantage of this approach is that the time-history of several variables can be displayed simultaneously, in a manner that is concise, visually effective, and reduces complexity, especially for patients and family members. The color-coding method effectively transforms the spatial representation of the results from a vertical dimension to a horizontal domain. The purpose of this paper is to describe the algorithmic development of the color-coding method. An example, based on an impaired subject's gait data, is reported and the advantages and disadvantages of the method are discussed.

## 2. Methods

Gait data for one patient having impaired gait were compared to normative data for 15 healthy subjects to demonstrate the color-coding method. Visual3D (C-Motion Inc., Rockville, MD, USA) was used to calculate sagittal plane ankle, knee and hip angles and moments during the stance phase of walking. All variables were interpolated to 101 data points representing 0%–100% of the stance phase. Data for the healthy subjects were averaged at every 1% of stance and served as normative values against which the patient data were reported. The normal subject data were collected in accordance with an IRB approved protocol at the Warren Grant Magnuson Clinical Center at the National Institutes of Health, Bethesda, MD. All normal subjects signed an informed written consent prior to their participation in the study. The patient data were extracted from a pool of clinical patient data deemed exempt from IRB review (under Appendix G, item number 4 of the multiple project assurance) by the office of human subject research at the Warren Grant Magnuson Clinical Center at the National Institutes of Health.

The deviation,  $d$ , at interval “ $i$ ” relative to the normal data is given by Eq. (1):

$$d_i = \frac{x_i - \bar{X}_i}{\text{S.D.}_i} \quad (1)$$

where  $x$  represents the patient data,  $\bar{X}$  is the normal value and S.D. is the standard deviation at  $\bar{X}$ . Thus,  $d$  is a normalized dimensionless quantity (i.e., Z-score) that corresponds to the magnitude of the deviation as a multiple of the S.D. A color based on the magnitude and direction of the deviation at point “ $i$ ” is assigned to every value for  $d$ . Negative deviations are color coded red, positive deviations blue, and for the purpose of this manuscript, values for  $d$  within  $\pm 1$  S.D. are color coded a shade of green to indicate that they lie within a normal range. The distribution of color as a function of  $d$  is illustrated in Fig. 1. Notice how the transition in color changes as a function of the deviation. That is, colors change slowly for values of  $d$  within a normal range (i.e.,  $\pm 1$ ), and more rapidly as the deviation increases in the neg-

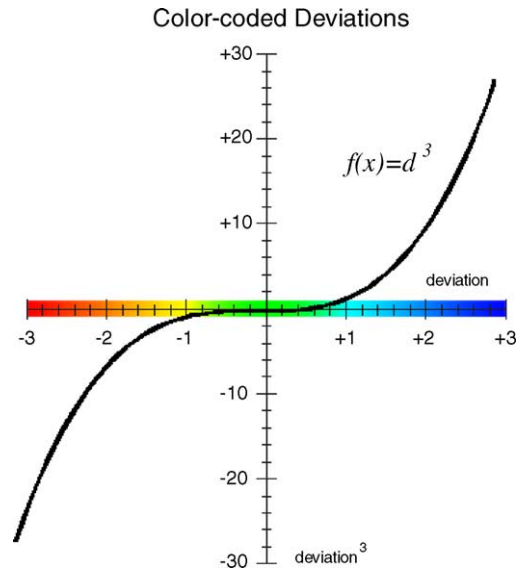


Fig. 1. Range of colors used to code deviations between patient's and normative values. Colors change as a function of the magnitude and the sign of the deviation. The function  $f(x) = d^3$  is superimposed on the spectrum of color. Note how the change in color increases as the deviation becomes increasingly positive or negative.

ative and positive directions. Colors are expressed numerically as an integer using the RGB color representation. The numerical equivalent of an RGB color is computed from the contributions of red (R), green (G) and blue (B) present in the color:








$$\text{RGB} = (R + G \times 256 + B \times 256^2) \quad (2)$$

Values for each component (i.e., R–G–B) range between 0 and 255. The larger the value, the greater the contribution to the resultant RGB color. Example R–G–B combinations, corresponding RGB values and resultant colors are reported in Table 1.

The smooth transition in color from red to blue in Fig. 1 was achieved by changing only one of the R–G–B components at a time. For example, the transition from yellow to green was the result of decreasing amounts of red (i.e., the magnitude of R decreases), while values for green and blue were held constant. In contrast, changes from green to aqua were the result of increasing the contribution of blue (see Table 1;  $0 \leq d \leq 1$ ). It is evident from Table 1 that the numerical values for the RGB colors do not increase positively across the range of deviations. For example, RGB values increase for values of  $d$  between  $-3$  and  $-1$ , and from  $0$  to  $+1$ . In contrast, RGB values decrease between  $-1$  to  $0$ , and  $+1$  to  $+3$ . These four sub-ranges will be referred to as sub-intervals 1–4 (i.e.,  $-3 \leq d < -1$ ;  $-1 \leq d < 0$ ;  $0 < d \leq 1$ ;  $1 < d \leq 3$ ), respectively. It is important to note that the RGB values within a sub-interval either increase or decrease, but the RGB values do not increase and decrease within a sub-interval.

A desired property of the color-coding method is that transitions in color increase as the deviation increases in a

Table 1  
Contributions of red (R), green (G) and blue (B) to the color assignments across a range (–3 to 3) of deviation values (*d*)

<i>d</i>	R	G	B	RGB	Color
–3	255	0	0	255	
–2	255	128	0	33023	
–1	255	255	0	65535	
0	0	255	0	65280	
+1	0	255	255	16776960	
+2	0	128	255	16744448	
+3	0	0	255	16711680	

The RGB value was determined from Eq. (2) in text and the corresponding color is displayed in the last column.

negative or positive direction. The function  $f(x) = d^3$  has the desired property of steep tails and a shallow mid-range consistent with the desired transition in color. However, the slope of the function cannot be used directly to generate the color spectrum depicted in Fig. 1 because the derivative of the function is positive and symmetric, while the RGB values increase and decrease across the –3 to +3 range of deviations. However, since only one component (i.e., R–G–B) changes within a sub-interval, the numerical equivalent of the constant components can be subtracted from the RGB value. In doing so, the value of the remainder will be increasing or decreasing, depending on the sub-interval in which the deviation lies. By inspection, we see from Table 1 that changes in color across sub-interval 1 (i.e.,  $-3 \leq d < -1$ ) were due to increasing values for (G); with decreasing (R), increasing (B) and decreasing (G) for sub-intervals 2, 3 and 4, respectively.

A quadratic polynomial was fit to the slope of the color function and the value of the color component at the end-points of each sub-interval.<sup>1</sup> This resulted in two unique equations. Eq. (3) was used to compute the value of the changing color component for sub-intervals 2 and 3 (i.e.,  $-1 \leq d \leq +1$ ), and Eq. (4) was used for sub-intervals 1 and 4:

$$C = 85f'_d \quad \{-1 \leq d \leq +1\} \tag{3}$$

$$C = 305.7 - 17.597f'_d + 0.2324f'^2_d \quad \{d < -1; d > +1\} \tag{4}$$

where  $f'_d = 3d^2$ , and *C* is the resultant value of the color component. For example, a deviation of –1.5 yields *C* =

197.508. Note that *C* must be converted to an integer before it can be used in Eq. (2). Since –1.5 lies in sub-interval 1, the color component *C* = 198 is assigned to G. The resultant RGB value for R = 255, G = 198 and B = 0 is 50,943. The color equivalent of 50,943 is a yellowish-orange, consistent with that expected from Fig. 1 for a deviation of –1.5. Values for *d* outside the ±3 interval were set to the closest extreme of the ±3 interval. The special case when *d* = 0 is given the RGB value 65,280 (R = 0, G = 255, B = 0). The value for *C* = 0 is assigned to the R and the B component.

### 3. Results

Fig. 2 depicts a customary time-history single variable example line graph consisting of normative and patient data for the ankle angle during the stance phase of gait. Superimposed on the abscissa is an example of the color-coding method derived from the displayed ankle angle data. The height of the depicted color-coded bar graph was arbitrarily set to a relatively small value in order to highlight an important fundamental characteristic of the color-coding method. That is, the color-coding method effectively transformed the depicted deviations from a vertical spatial dimension to a color-based range. This dramatically reduces the space required to display the magnitude and direction of deviations in the patient’s data from the normal values.

It is evident from the line graph in Fig. 2 that large negative deviations in the patient’s ankle angle occurred during the initial phase of stance, with the angle becoming increasingly normal as stance progressed. The color-coded deviations for the patient’s ankle angle depict shades of red as large negative deviations during initial stance, followed by

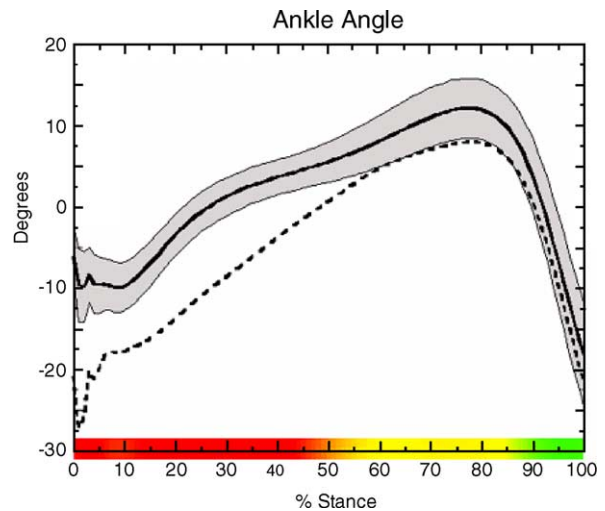


Fig. 2. Ankle joint angle data during the stance phase of gait for an impaired patient (dashed line) and the mean ±1 standard deviation (solid line and the shaded region) for 15 healthy normal subjects. The corresponding color-coded deviations between the subject and normal data are superimposed on the abscissa for comparison. Description of the color-coding scheme is contained in Section 2.

<sup>1</sup> Recall that only one RGB color component changes within a sub-interval. It is this component that is used in the polynomial regression.

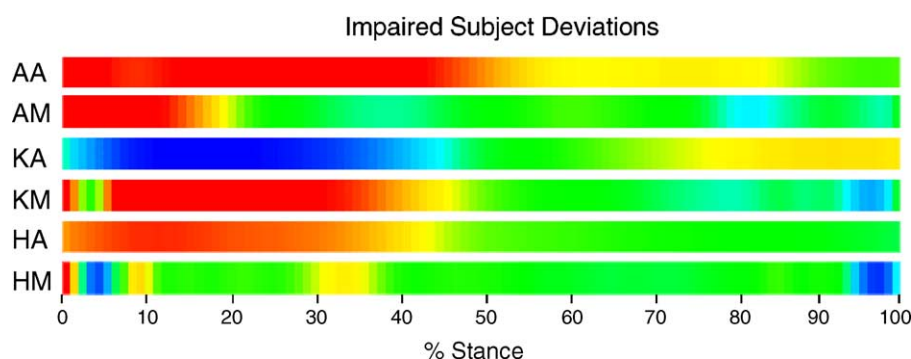


Fig. 3. Color-coded deviations for the patient's ankle, knee and hip joint angles and net joint muscular moments during the stance phase of gait. The first letter of the two character code corresponds to the ankle (A), knee (K) or hip (H) joint, with the second character indicating angle (A) or moment (M).

shades of yellow and green indicating an increasingly normal pattern.

The color-coded deviations for the patient's sagittal plane unilateral joint angles and moments for the ankle, knee and hip during stance are illustrated in Fig. 3. Customary time-history graphs for these variables have been omitted from the manuscript to conserve space. The extent of the red and blue shading during the first half of stance conveys that significant gait deviations occurred during this time, and that the ankle, knee and hip were all involved. In contrast, the latter half of stance was dominated by shades of yellow and green suggesting that the patient's gait progressed towards a normal pattern. Vertically arranging or stacking the bar graphs as presented in Fig. 3 effectively portrays deviations occurring at different joints and/or between variables. For example, it is easy to see that the hip moment was approximately normal during the entire stance phase, while significant negative deviations in hip position were noted during the loading response.

#### 4. Discussion

The purpose of this paper was to describe a novel method of data visualization. The method was presented in the context of clinical gait analysis. An advantage of this method is that the data are reduced to colored bar graphs and, thus, make it easy to compare the time-history of several variables simultaneously. A characteristic feature of the method is that the vertical spatial scale of the line graph is transformed to a horizontal bar graph of arbitrary height, thus making it possible to display a multitude of color-coded deviations on a single report page. For example, it is easy to conclude that the patient's movement patterns were approximately normal during the latter half of stance, with large deviations noted during weight acceptance (Fig. 3). In contrast, six line graphs of the patient's data plotted relative to normative values would have to be examined to draw the same conclusion.

The method presented herein is not without limitations. Perhaps the greatest drawback is that useful information is

lost when the data are reported as a deviation. For example, it may be of interest to know the magnitude of a patient's ankle angle at a particular point during stance. This information is not possible to obtain from the color-coded deviations. For this reason, we do not propose that color-coding the deviations be used in exclusion to other means of reporting data, but rather we see it as a useful adjunct to complement existing methods.

An important consideration is the sign convention associated with the anatomical motion of the joint. For example, we report knee flexion as a negative value, and therefore excessive flexion is shaded red. In contrast, other laboratories report flexion as a positive value, and consequently excessive flexion would be shaded blue. This is not a limitation of the method, but rather a reflection that there is no universal sign convention for displaying time-history data. Interpreting Fig. 3 with respect to our anatomical sign convention reveals that the ankle angle was excessively plantar flexed during the loading response, while the knee and hip were both in a greater extension than normal. This pattern is consistent with a patient that has knee extensor muscle weakness and concomitant weakness of the pre-tibial muscles.

A delimitation of the methodology was that the range of deviations reported in this paper was limited to  $\pm 3$ . The rationale for this range was that movement patterns outside these extremes are well beyond normal, and to differentiate between excessively large deviations means little from a clinical perspective.

The algorithmic development of the color-coding method was outlined in this paper. The method was applied to gait data obtained from a clinical movement analysis study. It is straightforward and easy to implement on a personal computer. Using the described technique, the deviations between any pair of time-varying signals can be color-coded as an effective means of data visualization and thus the method does not appear to be limited to clinical gait analysis or human movement studies. Future studies will examine the efficacy of color-coding a complete set of clinical data as a tool to complement existing data interpretation methods. It is hoped that the color-coding method will be used to facilitate the rapid and effective interpretation of clinical

movement analysis data and enhance patient education, awareness and increased participation in the important clinical decision making and outcomes assessment stages.

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